Laser Ranging to the Moon: How Evolving Technology Enables New Science

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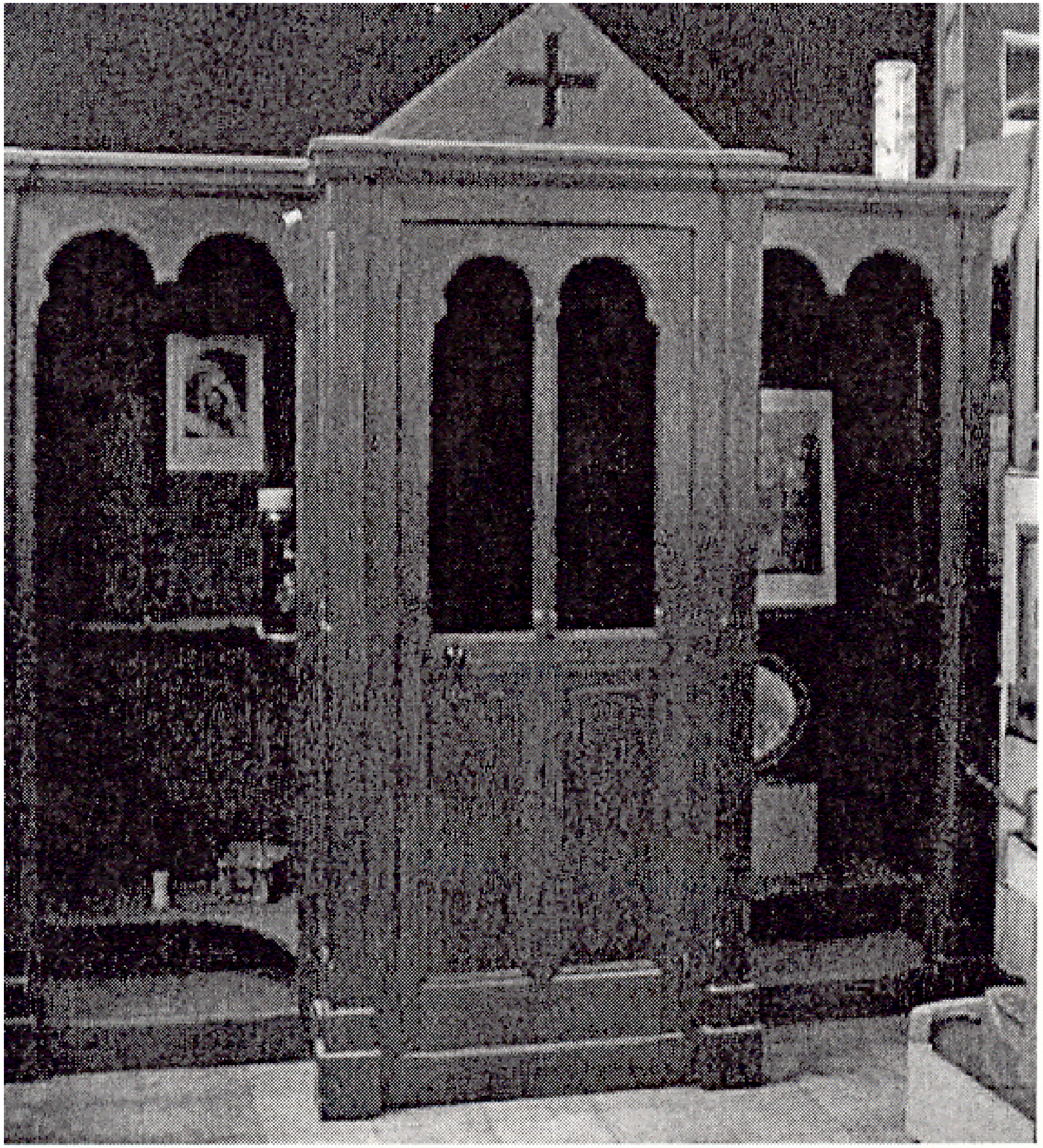
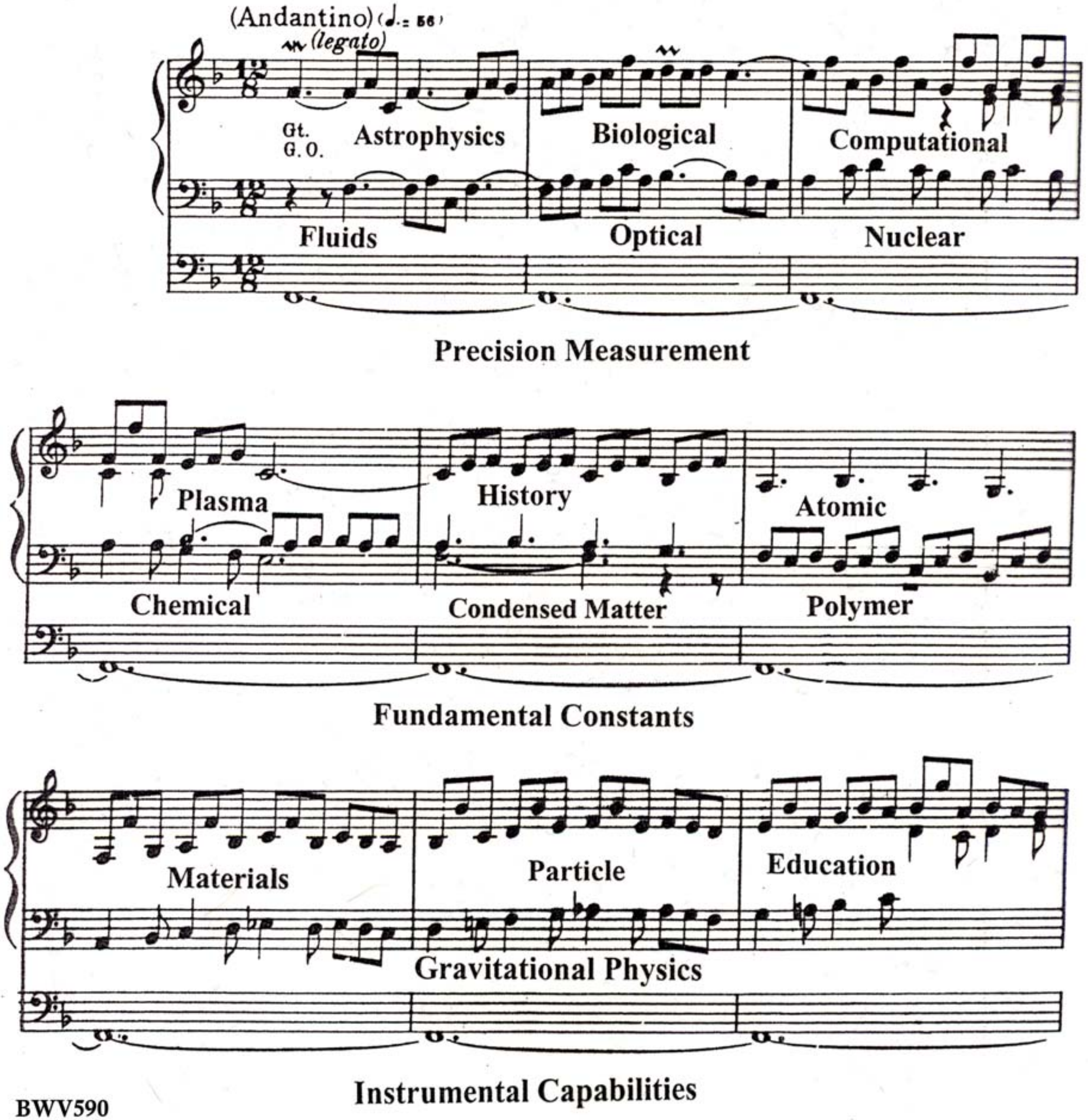
The Archives, University of Colorado at Boulder Libraries holds the James Faller Collection. The collection contains Dr. Faller's Lunar Laser Ranging papers etc. Currently, Archives personnel are surveying the collection to create an initial finding aid. For more information, please email <arv@colorado.edu>

In this special Laser Fest session, I was asked to talk about the origins of the Lunar Laser Ranging Experiment…and also how evolving technology, and in particular the laser, has enabled new science and new measurement capabilities. I also tried to address the issue of how this idea (and others) have come about. I have long recognized that new technological advances are the implementers of much of scientific progress.

- The viewgraphs presented here are all of the ones I had intended to show…some of which, however, I did not show as, for once, I talked much slower than when I had practiced the presentation. As a result, I had to quickly skip over mentioning our recently published big G experiment—a measurement that I had planned to discuss. This measurement of the Newtonian constant of gravitation offers yet another example of using lasers to make a "length measurement." In this case, a length change of much less than a wavelength of light was measured with high precision by using lasers to transform this (otherwise difficult) length measurement into the (much easier to work in) frequency domain. This was done by beating one laser that was locked to a hanging cavity (whose length could be "gravitationally changed") with another laser that was locked to a cavity whose mirrors were fixed at the hanging cavity's suspension points.
- In my scientific career I have come to realize that almost everything I have done stands on the shoulders of earlier experiments and experiences that I have either done or heard about—and that ever evolving technologies (such as lasers) have served me well in enhancing the sensitivity of my hands and the quickness of my eyes.



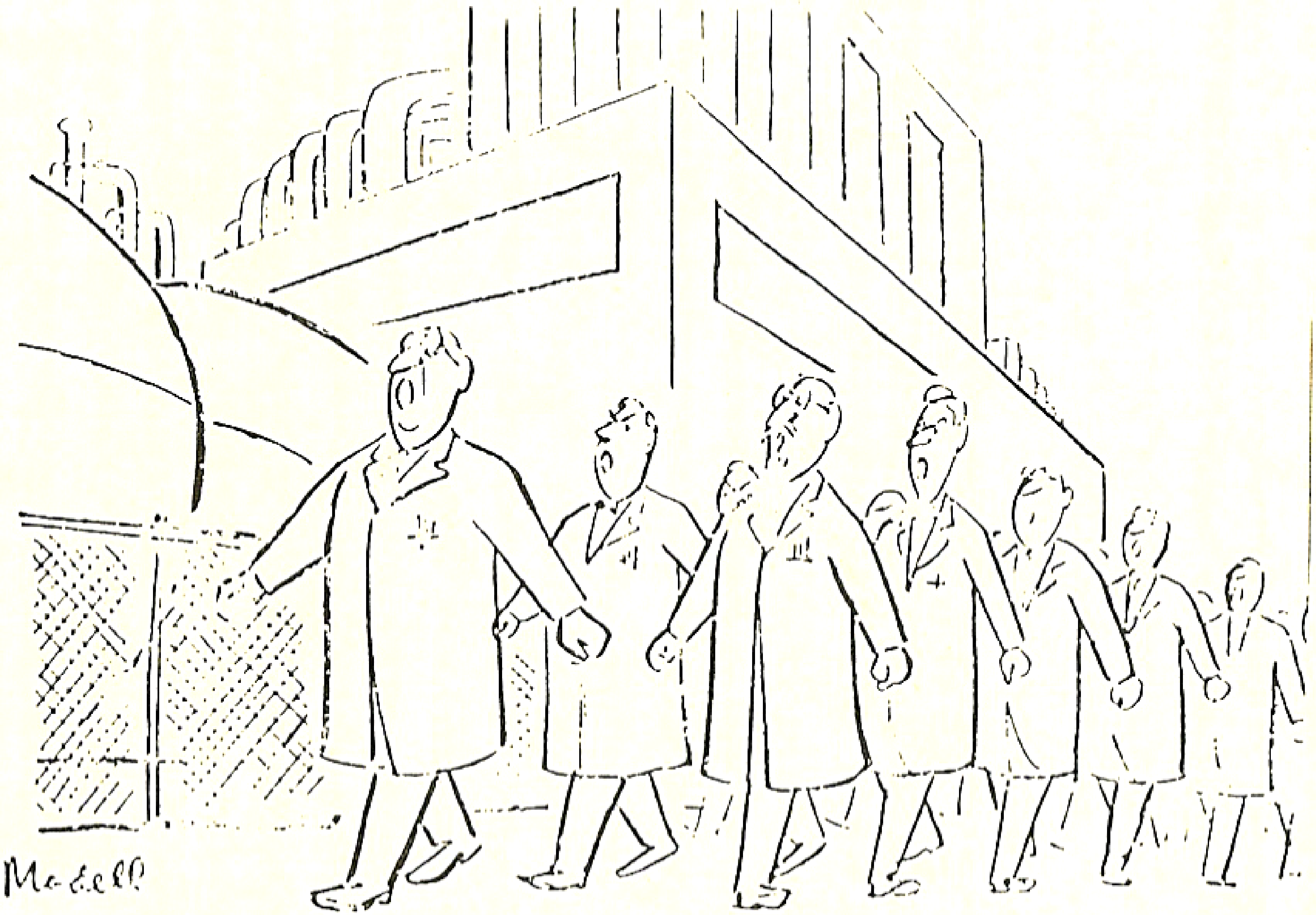
Pastorale



BWV590

Measurement Capability –
The Enabler of Scientific Progress

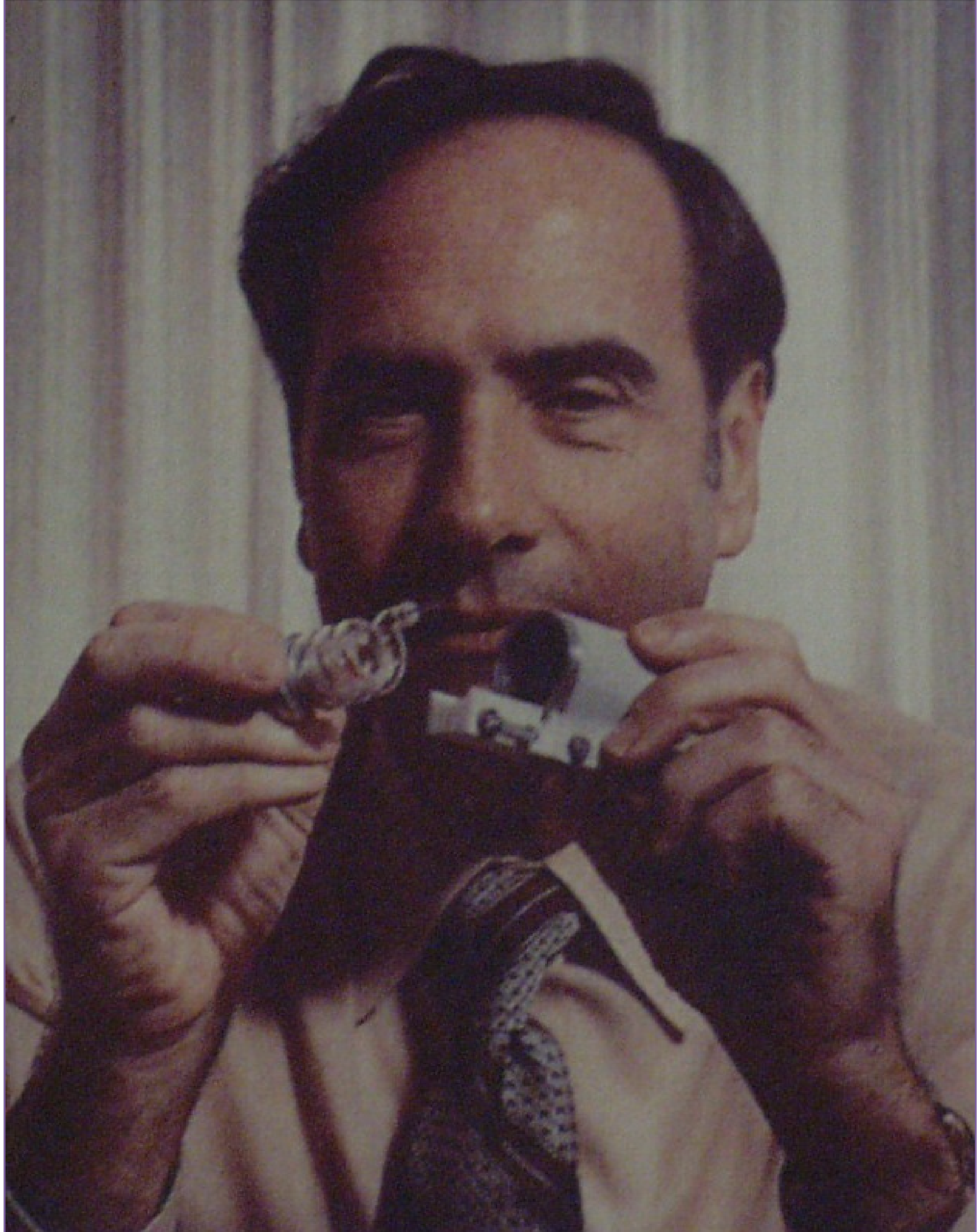
Precision Measurement~~s~~



"From the cyclotron of Berkeley to the labs of M.I.T.
We're the lads that you can trust to keep our country
strong and free."

Remembered Colloquia

- Wu (Columbia)…Parity Violation
- Weber (Maryland)…Gravity Waves
- R.V. Jones (Aberdeen)…Design of Apparatus
- Bohr (Copenhagen)…
- …
- Javan (MIT)…He-Ne Gas Laser



Dicke group evening meetings

Faller

NYO-2819

PRECISION OPTICAL TRACKING OF ARTIFICIAL SATELLITES *

W. F. Hoffmann, R. Krotkov and R. H. Dicke
Palmer Physical Laboratory, Princeton University

July 15, 1959

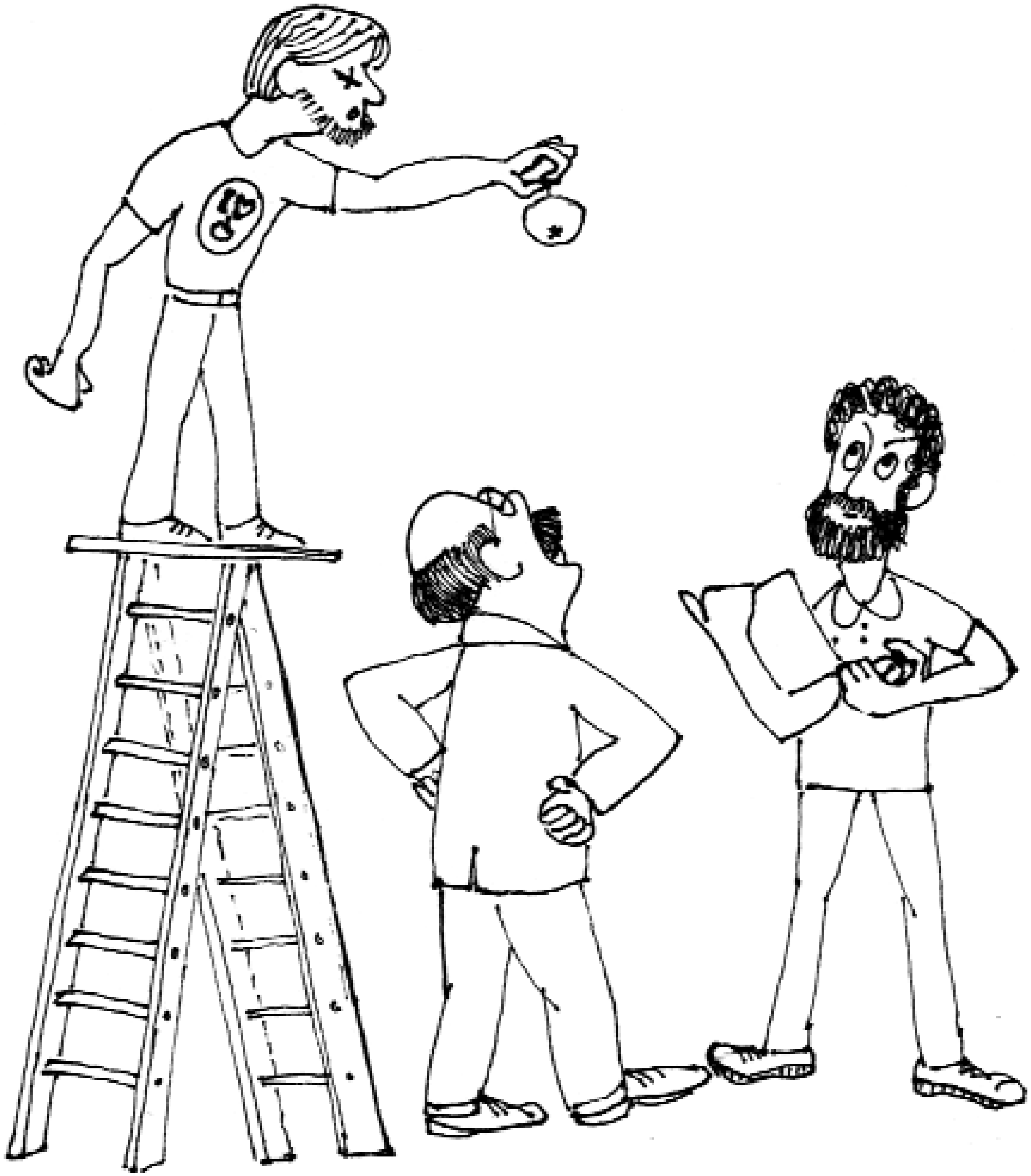
INTRODUCTION

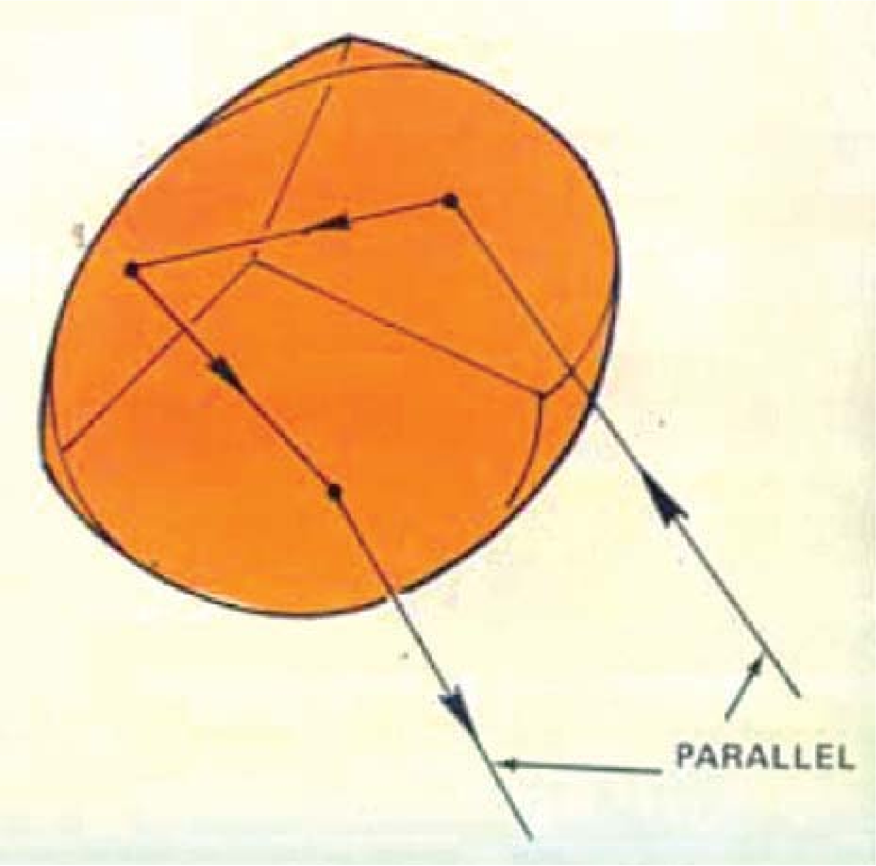
The authors are serving as a committee for the whole group to study the problem of instrumentation for precision optical position measurements of artificial earth satellites. Our interest in this problem concerns the use of artificial satellites for precision experiments on gravitation. These interests were briefly described in a letter to Dr. Clemence of the Naval Observatory, dated May 8, 1959. A copy of this letter is attached.

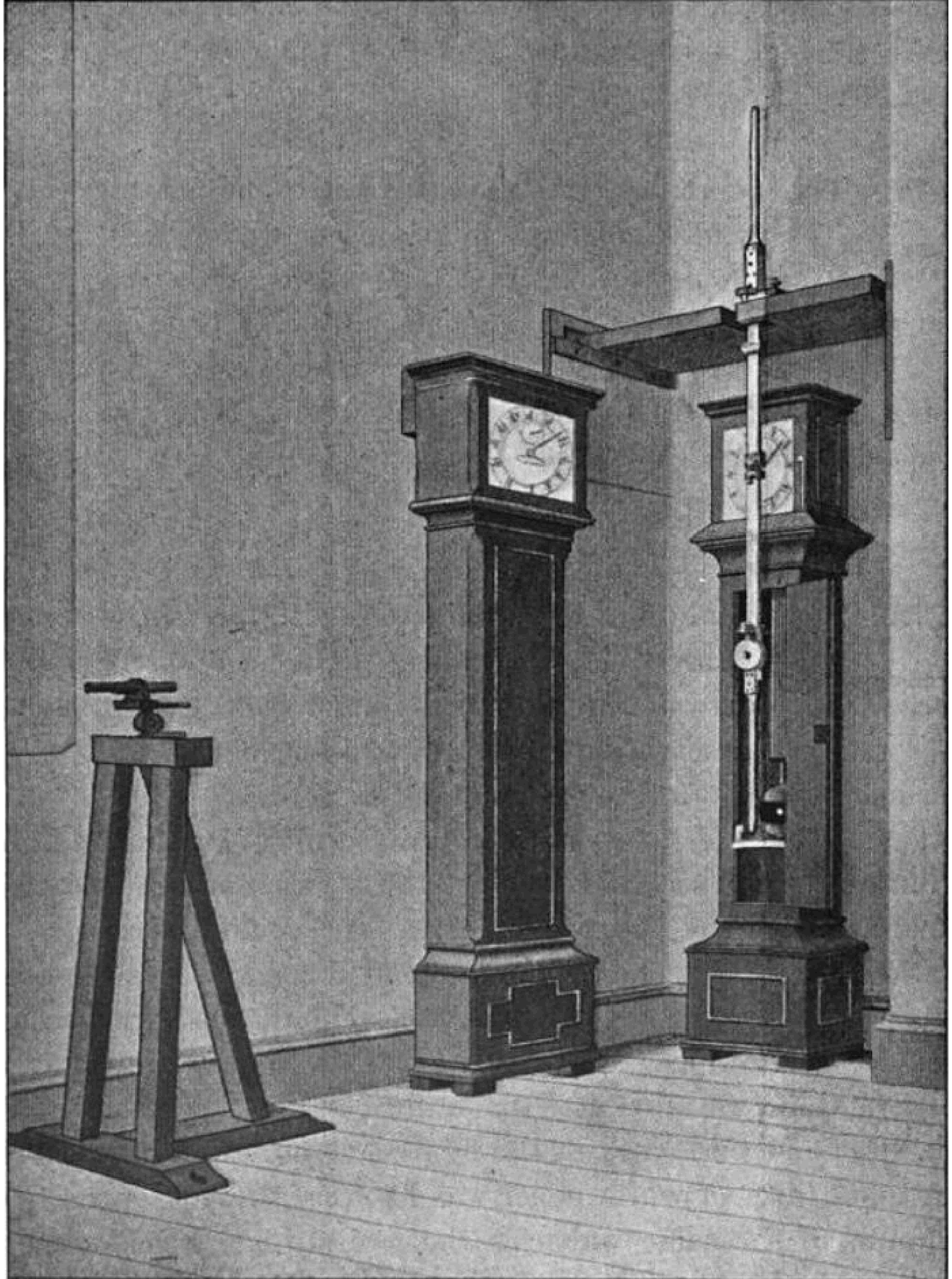
The following ideas are not wholly those of the authors, but in part are due to the whole group: J. Brault, R. H. Dicke, J. Faller, W. Hoffmann, L. Jordan, R. Krotkov, S. Liebes, R. Moore, J. Peebles, J. Stoner, and K. Turner.

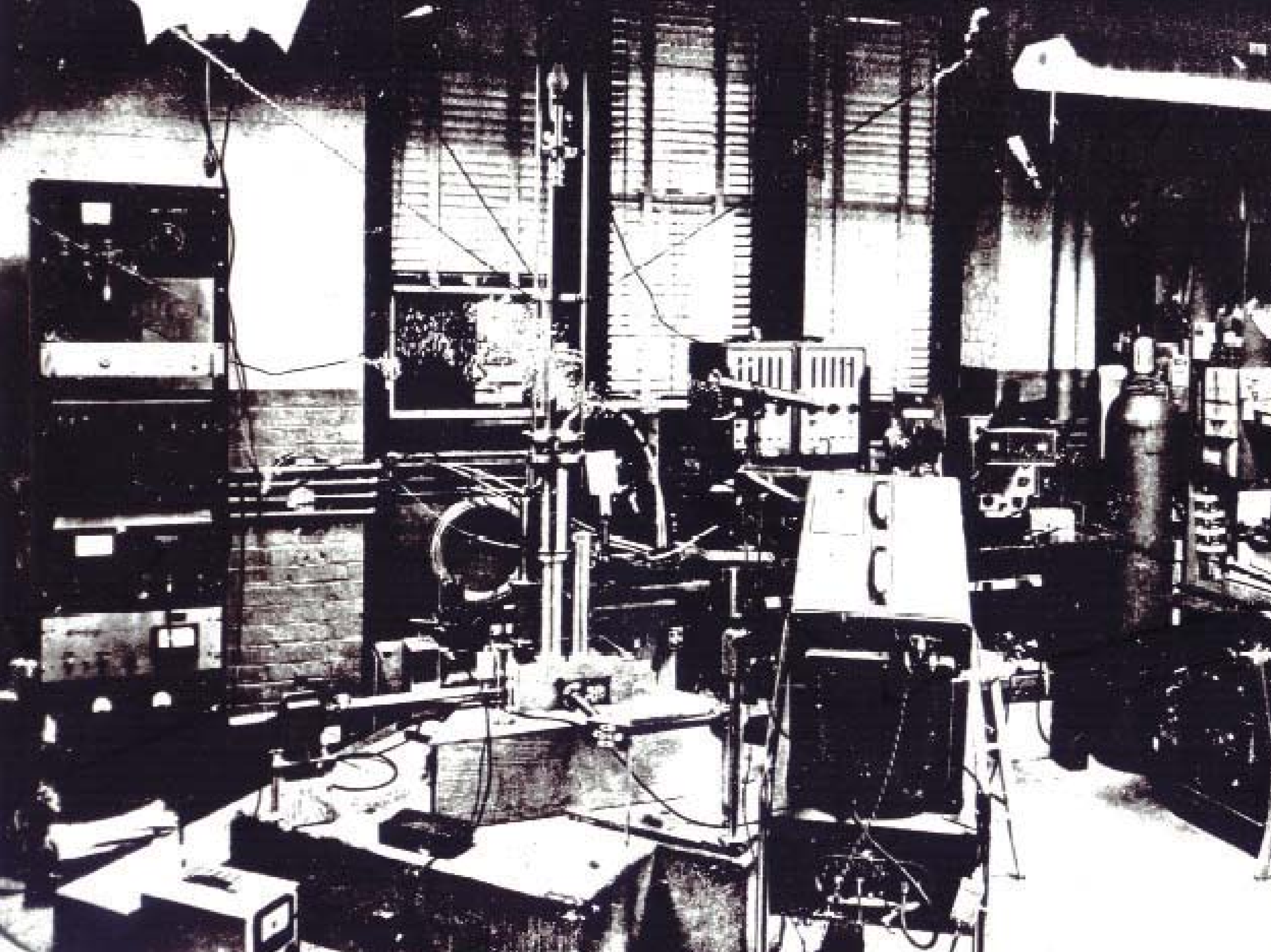
The precision tracking of a satellite reduces to determining its position relative to axes fixed in the earth or relative to the star field. There is a substantial advantage in determining position relative to the star field as this removes systematic errors associated with thermal tilt in telescope mountings.

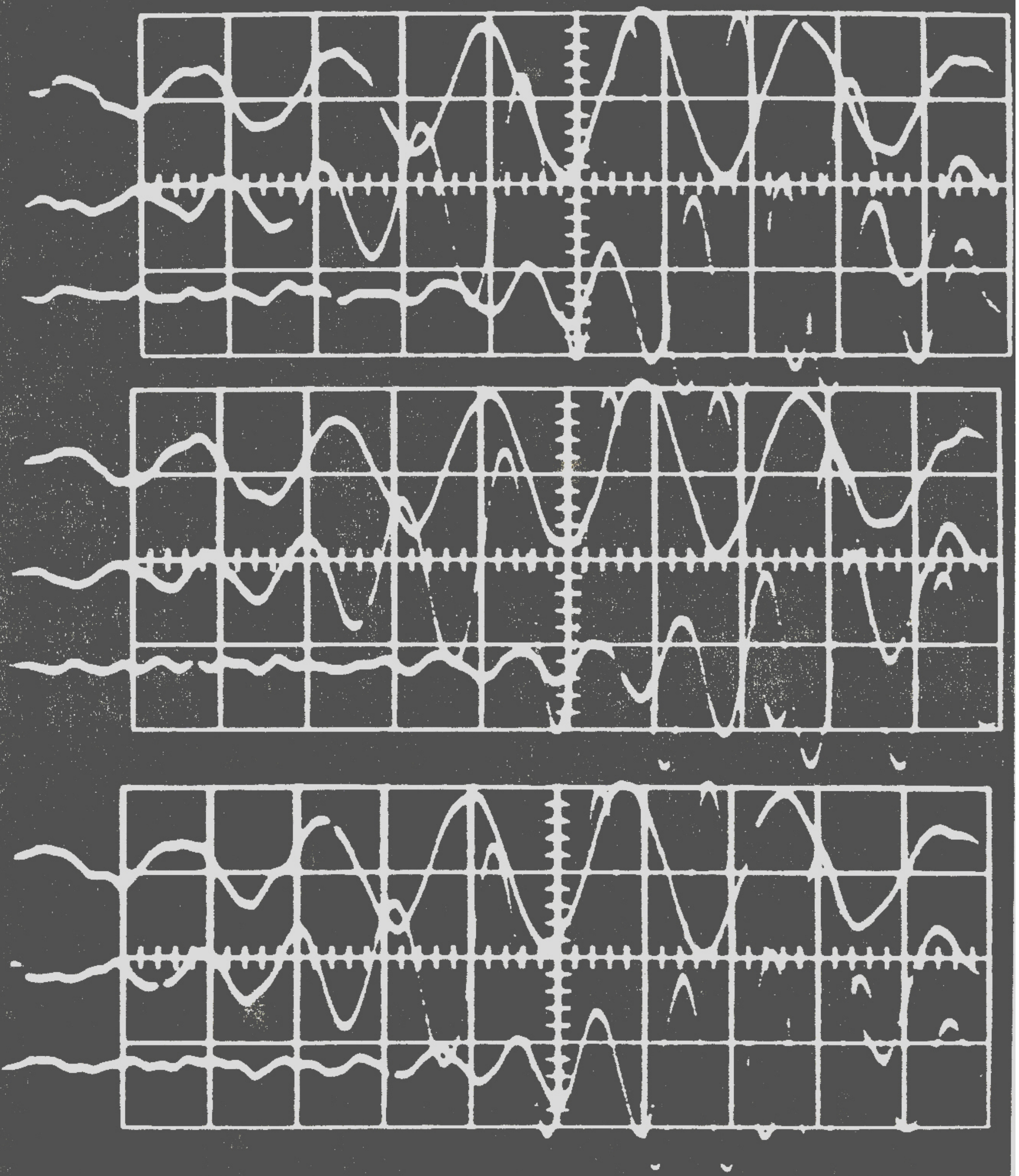
In the techniques to be discussed the background star field is recorded photographically. A photographic recording of the satellite position is employed when a sufficient number of photons is available. When the number of photons




PARALLEL





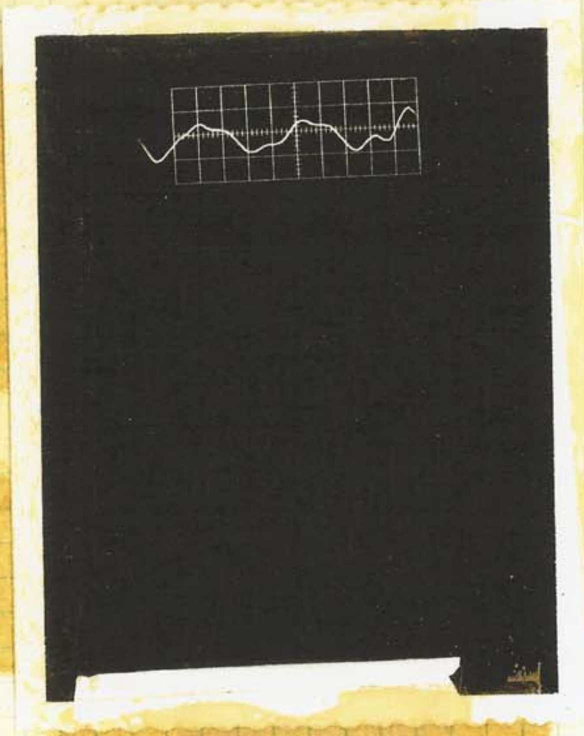


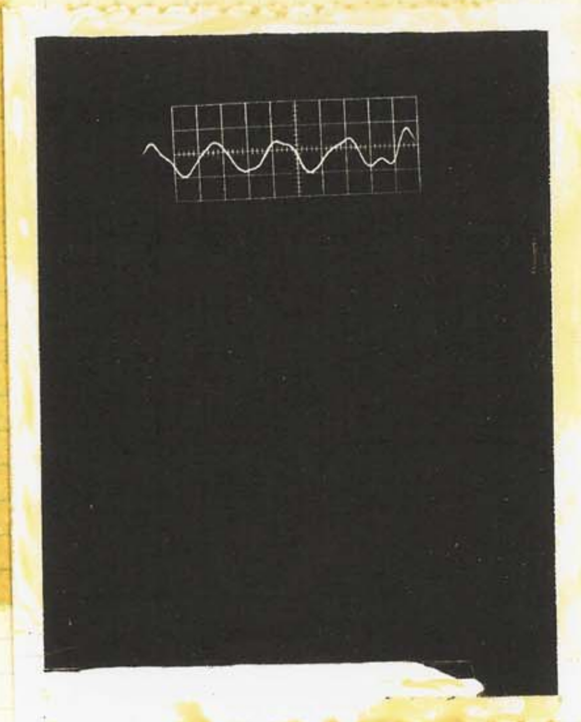
1962

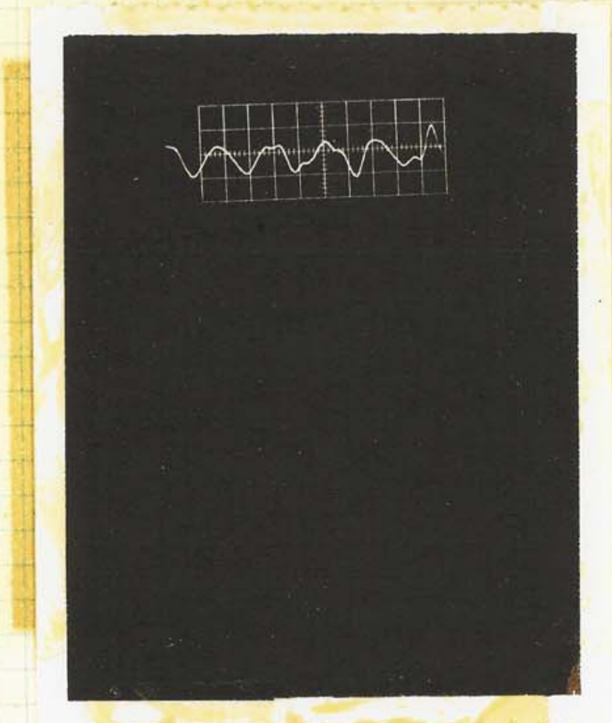
(early Oct 15)

Oct ?

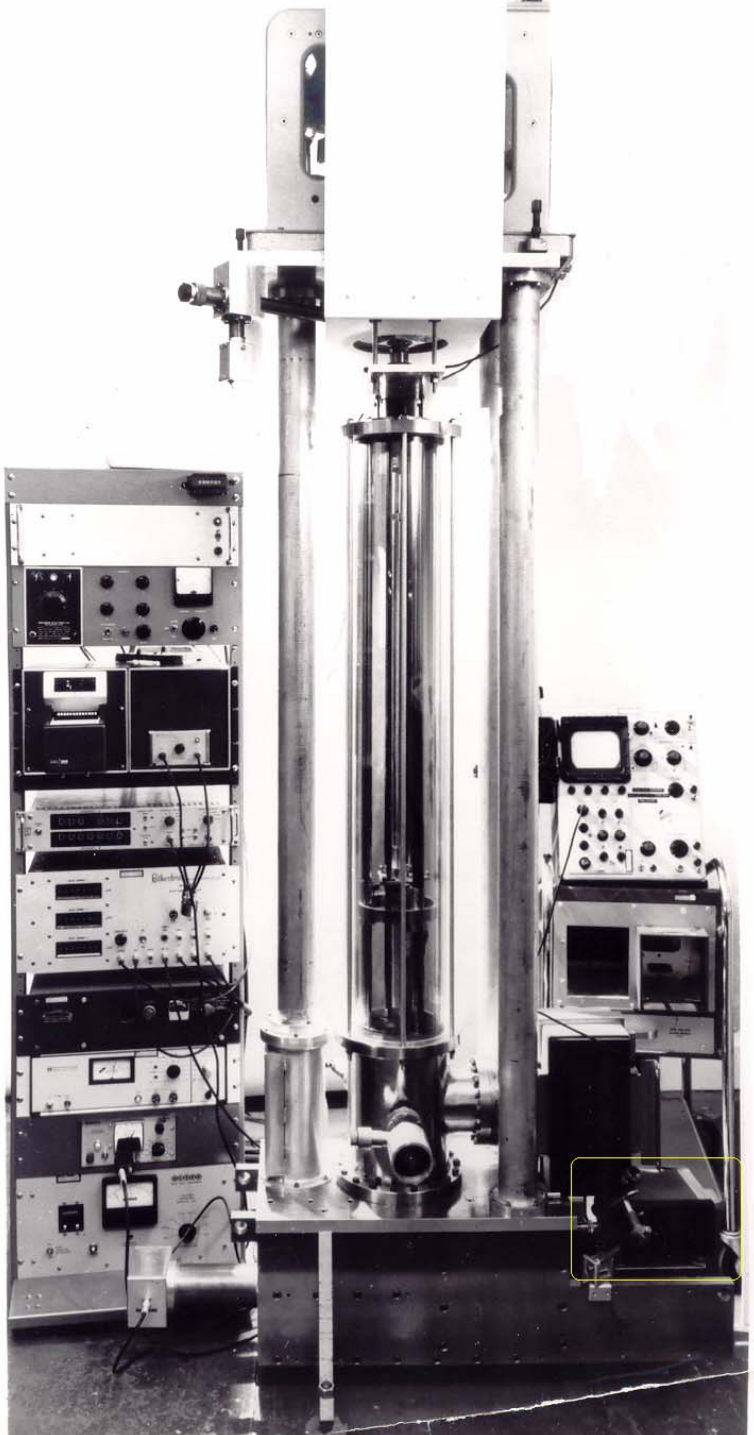
He-Ne Laser @ 6328 Å

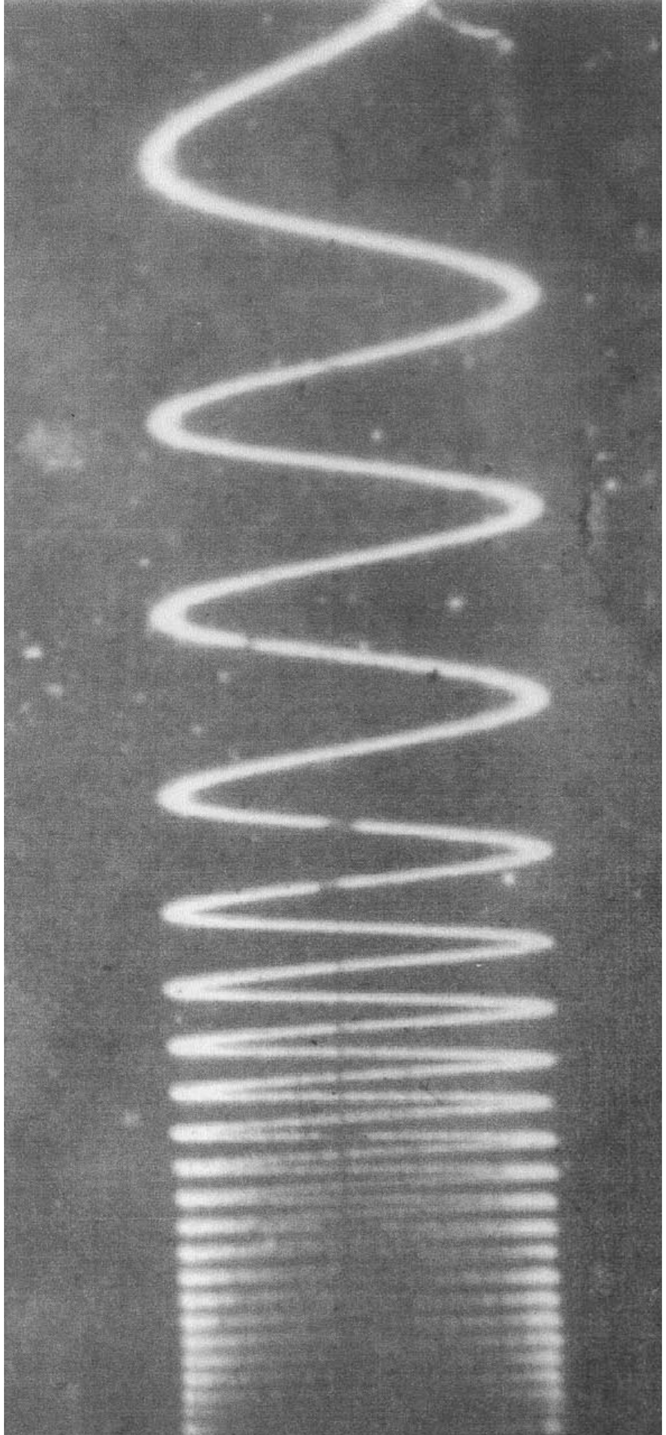

~ 2.4 Mc

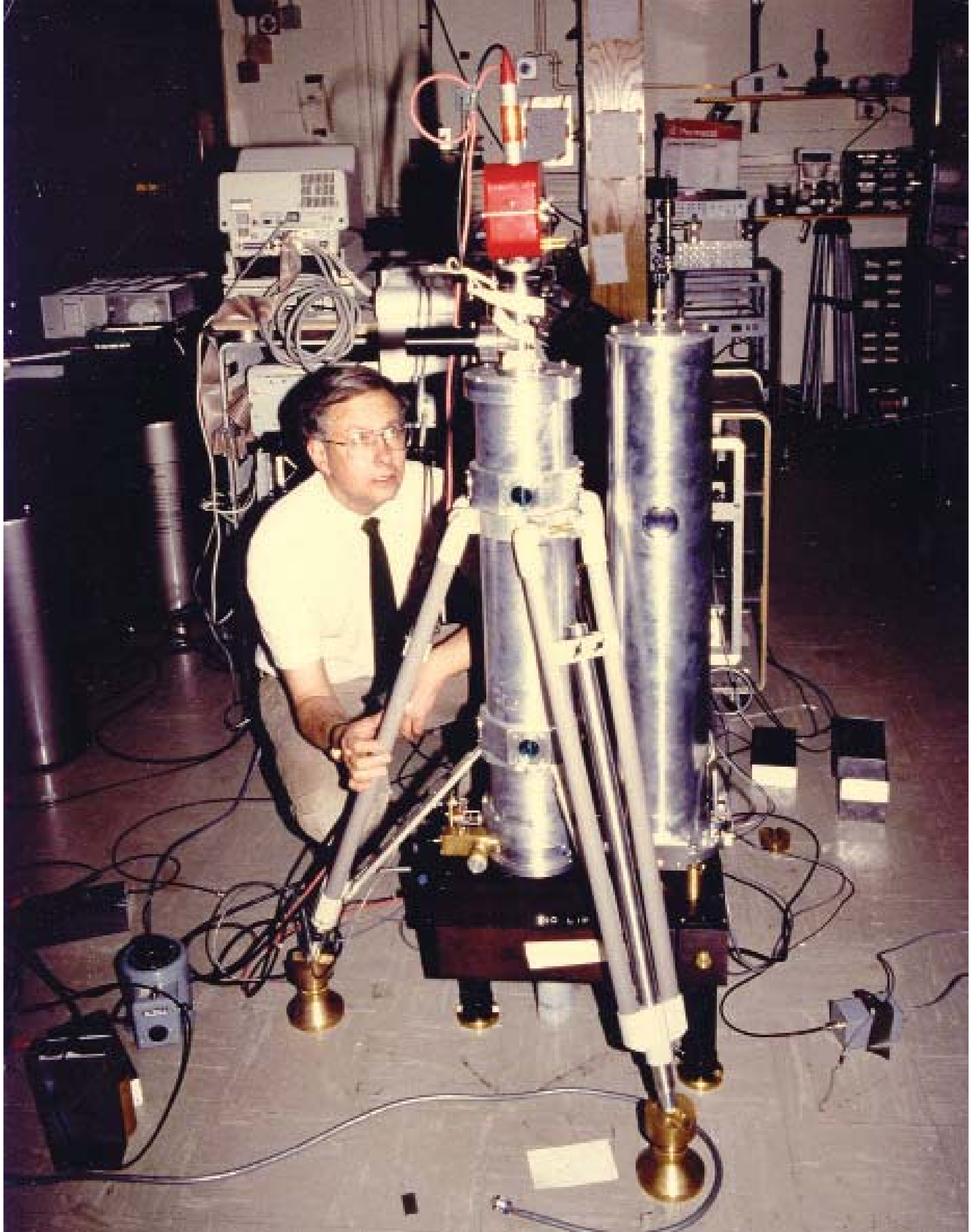

~ 3.5 Mc


~ 4.3 Mc

"Fringe" results from triggering scope through band-pass filter (scope set for single sweep)
First sniff thru filter trigger scope: Bandpass filters used ~ 2 Mc wide, center
frequencies 2.7, 4.0, + 4.9 Mc








Micro g LaCoste

I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project...will be more exciting, or more impressive to mankind, or more important...and none will be so difficult or expensive to accomplish...".

President John F. Kennedy, May 1961

Perhaps we could
discuss this.
Bob D.

Professor Dicke,
Would you see if this makes
any sense.
Jim Faller

A Proposed Lunar Package
(A Corner Reflector on the Moon)

This note describes what is felt to be both a useful and at the same time a practical lunar package. The total weight involved would be only 2 to 3 pounds, and it could be construted to withstand a rather hard landing. Once there, the only requirement for it to function successfully is that its landing leave it free to bounce and roll until it comes naturally to rest. This lunar package containing an optical corner has been built.

Recently there has been considerable discussion concerning the possibility of bouncing a laser off the moon and detecting the reflected light returning to the earth. This would permit a precise earth-moon distance measurement to be made. (The distance here being measured to one of the larger maria.)

In order for this to be done, a rather large aperature is needed to collect the reflected photons as is seen from the following calculation: 30 joules/laser burst ~ 10^{20} photons/burst

All the photons will hit the moon and scatter back into a solid angle of approx. 2π steradians. The number of ~~reflected~~ the reflected photons that will be collected is given by

$$\frac{\text{solid } \angle \text{ of collector}}{2\pi} = \left(\frac{30}{4\times10^{10}}\right)^2 \Big/ 2\pi$$

if we use a 12" (30 cm.) telescope. Assuming 1/10 of the photons which hit the moon are reflected, the number collected by our telescope will be:

$$10^{20} \times \frac{1}{10} \times \frac{30^2}{(4\times10^{10})^2} \times \frac{1}{2\pi} \sim 1 \text{ photon/laser burst.}$$

which is not very encouraging. (With a 100" telescope one collects ~ 81 photons/laser burst.)

The lunar package proposed here would permit a substancial improvement to be made in the number of returning photons that are collected. First note that for a <u>fixed payload</u> (all other things being equal) it would be best to put a single large corner on the moon rather than a lot of smaller ones. This may be seen as follows: $\text{Number of corners} \sim \frac{1}{l^3}$ $(l = \text{linear size})$

$$\text{Collecting area for light offered} \sim \text{Number of corners} \times l^2 \text{ or } \sim \frac{1}{l}$$

The size of the sopt on earth resulting from diffraction in the corners affecting the returning photons is given by

$$\left\{2 \times \frac{\lambda}{l} \times (\text{Earth-Moon Distance})\right\}^2 \sim \frac{1}{l^2}$$

It therefore follows that the efficiency which is proportional to collection area on moon/diffraction area on earth $\propto l$.

Therefore ~~So~~ it is better, so to speak, to put all the photons in one corner. In practice (to minimize the possibilities of landing mishaps) it would be best to place several corners one the moon rather than "the ideal" single corner reflector.

A one-pound corner cube (the one used in the model package) offers a collection area of apporx. 40 cm^2. Using a 12" (30 cm.) telescope to set the diffraction size of the spot on the moon (an idealization neglecting practical difficulties both in reference to actual lasers and to atmospheric disturbances), the area on the moon is given by:

$$\left(2 \times \frac{8\times 10^{-5}}{30} \times 4\times 10^{10}\right)^2 \sim 3 \times 10^{\overset{12}{10}}\ \text{cm}^2$$

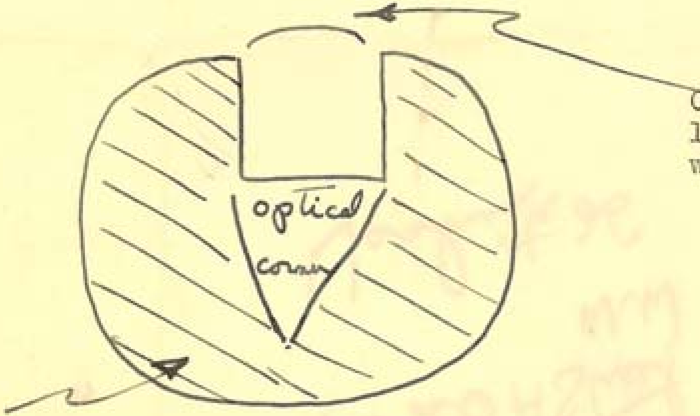
The number of photons returned will be those collected, namely:

$$\frac{40}{3\times 10^{10}} \times 10^{20} \sim 10^{11} \text{ photons/burst}$$

These will form a larger patch on the earth due to the smaller size of our corner (compared to our 12" telescope), but ~~not~~ now we have a larger photon collecting area. The net effect of this is that we again ~~lose~~ ~~loose~~ lose by the same factor, namely 10^{-9} resulting in 100 photons being collected in this case. Here, in principle, the number of photons collected goes as the forth power of the telescope aperature so that going to a larger telescope is even more useful ~~then~~ than in the case of bouncing photons simply off the moon where improvements are only proportional to the square of the aperature.

In addition to permitting the afore-mentioned experiment, a group of corners on the moon would provide the long-desired marking stripes on the moon and thereby permit precise period measurements to be made. The moon would then be a precision gravity clock.

Proposed package (cross section)



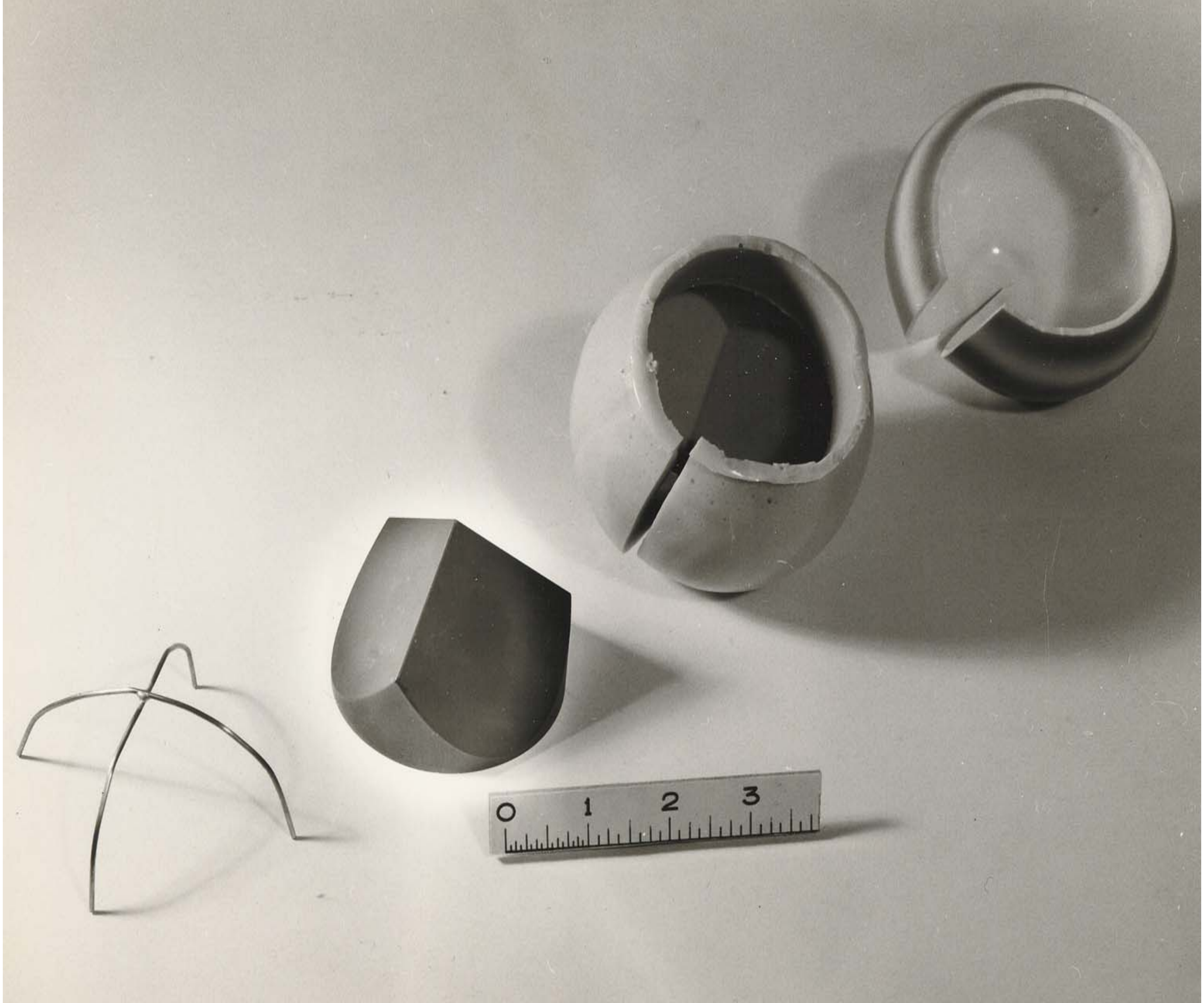
Cross wires to prevent
landing (and staying)
wrong side up

Rubber

Note that the COM is arranged to be below the center of the ball when the corner is properly positioned, and therefore the package will position itself with the corner pointing up.

“A month or two in the laboratory will save you an hour in the library.”

Experimental Physicist Moto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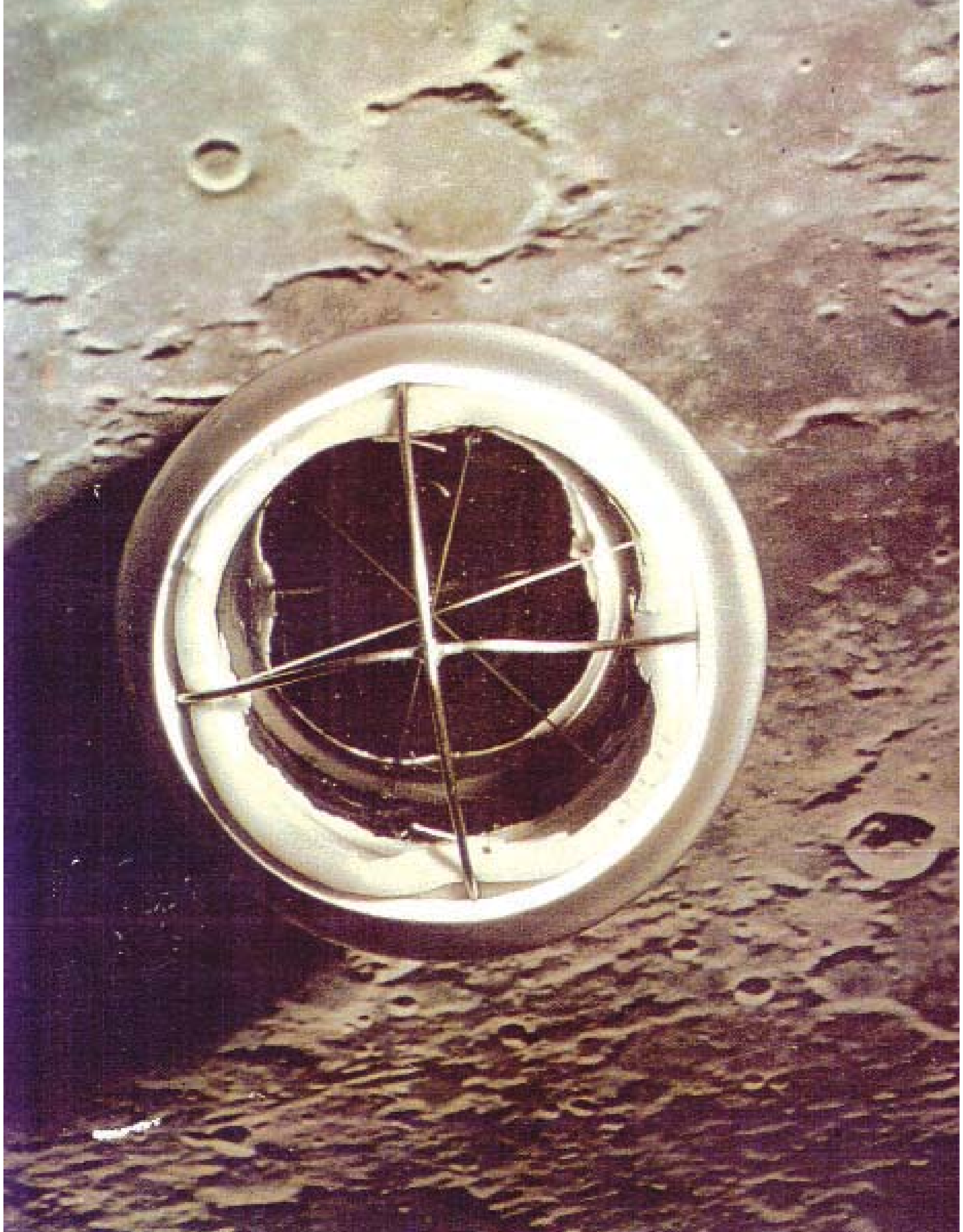

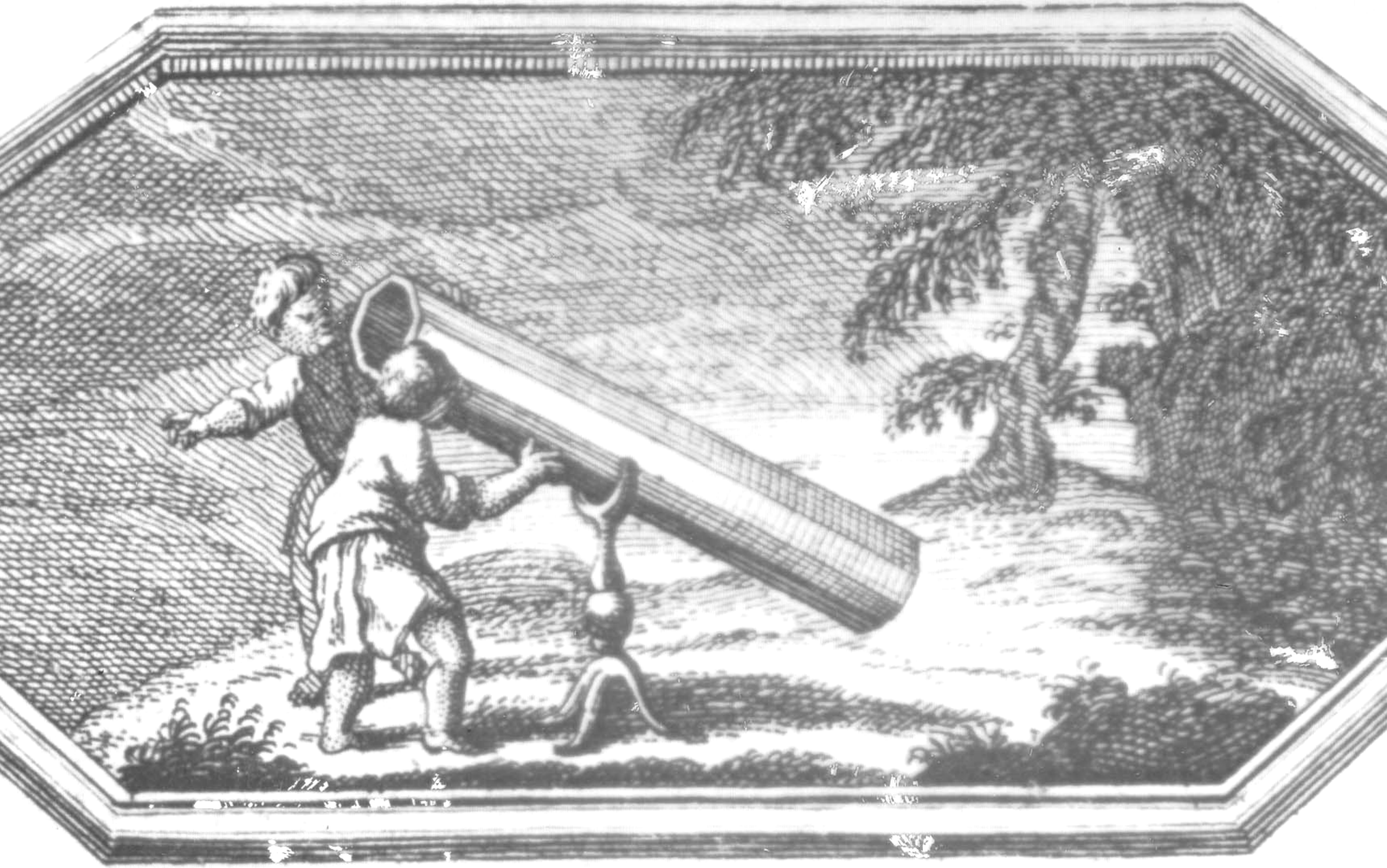
1773

July 1962

Project Luna See*

In order to determine some of the possibilities of optical maser radar we conducted experiments with the Moon as a target.

Predicted Performance

The basic system was conceived as consisting of a pulsed transmitter and a receiver. The transmitter was to be a ruby maser, radiating at 6934Å, and focused by a 12-inch reflecting telescope. The receiver was to be a photomultiplier tube illuminated by light collected in a 48-inch reflecting telescope. The photomultiplier output was to be displayed on a suitably delayed oscilloscope trace (the A-type radar display).

If the light from the ruby were perfectly coherent over the cross section, and illuminated the 12-inch telescope uniformly, the beam divergence, given by λ/D, would be about 2×10^{-6} radians. Even allowing for a beam width 100 times greater, the resulting spot on the Moon, at a range of 200,000 miles, would constitute a point source for re-radiation to the Earth. Thus, if we assume the reflected light to obey Lambert's law, we get a modified "radar" equation, in which the received light energy W_R at the photocell varies as R^{-2} instead of R^{-4}.

$$W_R = W_T \frac{A\rho}{\pi R^2} K_a^2 K_T K_R$$

where A is the area of the receiving aperture, R is the distance to the Moon, W_T is the energy of the transmitted pulse, K_a is the transmission through the atmosphere, K_T and K_R are the optical efficiencies of the receiving and transmitting system respectively, ρ is the normal albedo of the lunar surface. We estimated (or knew) the constants of our system to have the following values: $A=1$ m², $K_T=0.75$, $K_R=0.37$, $K_a=0.85$, $\rho=0.15$ (for a bright spot on the Moon), $R=384{,}000$ Km, and thus $W_R/W_T \approx 6.5\times10^{-20}$. If $W_T=50$ joules at $\lambda=6934$ Å, there would be about 12.5 photons incident on the detecting photosurface per pulse.

Competing with our own signal are three noise sources: the dark current emitted by the photosurface, the ambient light from the lunar surface, and light scattered in the atmosphere and the telescope. Manufacturer's data indicated dark currents for a cooled photomultiplier corresponding to about 10 photoelectrons/sec. Since the maser pulse is about $\frac{1}{2}\times10^{-3}$ sec in duration, the expected, received photon flux is of the order of 2.5×10^4 photons/sec. At 6900 Å the efficiency of the photo surface is about 3 per cent, so that the expected signal component is about 750 photo electrons/sec. Thus, the dark-current noise was expected to be negligible. At night, and aiming at the dark side of the Moon, the principal interfering sources are the Earthlight and the scattered light of the crescent. The new Moon appears in the sky too early in the daytime, with a consequent high level of scattered light in the atmosphere. In addition the earthshine on the dark portion of the Moon is maximum at new Moon. Near full Moon, the dark portion of the Moon is darkest, but the large amount of light scattered from the sunlit surface would make operation very difficult. The brightness of the dark side of the Moon varies by about a factor of 15 from just after new Moon to shortly before full Moon (a variation of 100° in phase).[1] From published data[2] it is estimated that the power density in the visible range, incident on the Earth, reflected from the dark side of the Moon at first quarter, is $S=3.3\times10^{-15}$ watts/m² $\times$(km² of Moon area). In a bandwidth of 7 Å, centered at 6934 Å, this corresponds to a power density of about 0.7×10^{-17} watts/m²km², or about 28 photons/sec (meter)² (kilometer)². Existing estimates of scattered light indicate an intensity 1 to 10 times greater than the above number.

The field of view of the receiving system was assumed to be limited by an aperture to an area on the Moon of about 5000 km². Thus the background signal received by our 1 m² telescope was expected to be about 1.4×10^5 photons/sec due to Earth light, plus a component up to 10 times greater due to scattered light. Assuming 5×10^5 photons/sec, and then including K_R and K_a, we find a "noise" flux of 160,000 photons/sec incident on the photocell. The maser pulse duration is about $\frac{1}{2}\times10^{-3}$ sec, and thus the expected background photon flux per pulse length would be about 80, and might be as low as 30.

These numbers indicate that the signal-to-noise ratio to be expected, for the parameters chosen, might be of the order of 0.5 or less.

Description of the Apparatus

The telescope used for transmitting was of a Cassegrainian reflecting type, focal length 4.55 meters, aperture 0.29 meter (12 inch). The maser unit, except for small modifications to the cooling system, is as described by Bowness, Missio and Rogala. (See next communication, this page.) Each of the four flashlamps is connected through a 0.3-mH choke to an 840-μF bank of capacitors, charged to 2200 volts. In laboratory tests the output of the maser, as measured with a calorimeter, was observed to be about 50 joules. Since the cooling in the telescope installation was improved over that used in the above tests, the actual radiated energy may have been somewhat greater. The maser beam is focused (Fig. 1) by a lens of 102-mm focal length onto the focal plane of the transmitting telescope. Measurements were made of the size of the focused spot by burning holes through an aluminum foil. The resulting holes had a diameter of about 0.9 mm. If the hole size is assumed to indicate the image size, the beamwidth radiated by the telescope is 0.2 mrad, maximum. The receiving telescope (Fig. 2) was also a Cassegrainian reflector of focal length 18.2 m and collecting area of 1.00 m² (48-inch diameter).

A dichroic mirror was used to separate the red part of the spectrum so that the residual green light could be used for viewing through an eyepiece. The red portion of the spectrum passed through a camera shutter and iris assembly at the focal plane, and was then collimated by a lens. The adjustable iris allowed us to modify the field of view accepted by the photomultiplier. Throughout the experiments the diameter of the circular opening of the diaphragm was 3.6 mm, equivalent to a field of view of 0.2 mrad. After the diaphragm and lens the red light passed through a combination of blocking filter and narrow-band tunable interference filter having a bandwidth of 7Å.[3] The filtered light fell on the surface of an EMI 9558-A photomultiplier tube which was cooled to liquid nitrogen temperature. The signals from the photomultiplier were preamplified and then displayed on one trace of a double-beam oscilloscope. On the second trace, timing signals from a Time Mark Generator were displayed. The 20-msec sweep was delayed by about 2.6 seconds, differently on each night according to the distance to the Moon. Each trace was photographed. The distance to the Moon was computed with the aid of Ephemeris data.

In order to obtain accurate synchronization between the maser pulse and the delayed sweep, the firing was initiated by a 1-sec repetition rate trigger pulse, derived from the timer and gated by a push-button circuit. This trigger pulse also activated the delayed oscilloscope sweeps.

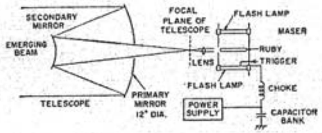

Fig. 1—Simplified diagram of transmitter.

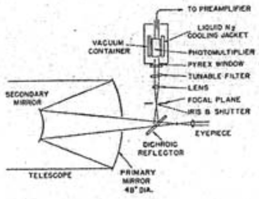

Fig. 2—Simplified diagram of receiver. The interference filter was tuned by rotating its plane with respect to the optical axis of the system.

Results

The experimental results are summarized in Table I. The experiments are grouped in four series. The number of consecutive flashes in each series is given in column 3. Column 5 gives the average signal level (number of counts) obtained in a ½-msec interval, due to Earth light and scattered light. The average was computed from actual counts in ½-msec intervals at time delays different from the expected round-trip time delay of the signal. Column 6 gives the standard deviation of the background level. The total number of intervals used in establishing the background is given in column 4. Column 7 gives the average photoelectron count obtained in that 0.5-msec interval where echoes were expected, and is therefore a measure of the signal-pulse noise.

It is evident that signal-pulse noise (column 7) exceeds the average noise by a significant amount in all the experiments, but especially in the first and last ones. After completion of the experiments there were no signs of damage to the various optical elements of the transmitter. The focusing lens of the maser showed slight evidence of dust burned into the anti-reflecting coating.

TABLE I

1 Eastern Standard Time	2 Region of the Moon	3 Number of Flashes	4 Number of Intervals	5 Average Noise	6 S.D.	7 Average Count in Expected Interval
May 9, 1962; $21^{h}56$–$22^{h}07$	Albategnius 15°S8°E	11	15	1.11	0.28	1.91
May 10, 1962; $21^{h}52$–$22^{h}34$	Copernicus 10°N20°W	23	16	1.39	0.22	1.74
May 11, 1962; $21^{h}57$–$22^{h}50$	Tycho 43°S10°W	30	22	1.42	0.16	1.83
$22^{h}54$–$23^{h}15$	Longomontanus 50°S20°W	16	17	1.52	0.19	2.32

We wish to acknowledge the help of J. Daley, Jr. of Lincoln Laboratory in the adjustment and use of the telescope; of G. Hardway and S. Kass of Raytheon Company in the testing and use of the maser; and of G. McGrath of Lincoln Laboratory in computing the Ephemeris data.

L. D. Smullin
G. Fiocco
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Mass. Inst. Tech.
Cambridge, Mass.

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* Received June 4, 1962; revised manuscript received, June 7, 1962. This work was supported in part by the U. S. Army Signal Corps, the Air Force Office of Scientific Research, and the Office of Naval Research.

[1] A. Danjon, "Albedo, color and polarization of the Earth," in "The Solar System," vol. II, G. P. Kuiper, Ed., The University of Chicago Press, Chicago, Ill.; 1954.

[2] M. Minnaert, "Photometry of the Moon," in "The Solar System," vol. III, G. P. Kuiper and B. Middlehurst, Eds., The University of Chicago Press, Chicago, Ill.; 1961.

[3] The filter was manufactured by Thin Film Products, Inc., Cambridge, Mass.

* Received June 4, 1962.

In 1963 moved to JILA where I told Peter Bender and Jan Hall about my idea for lunar laser ranging.

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A Prototype Lunar Transponder

MAHLON S. HUNT

Air Force Cambridge Research Laboratories
Bedford, Massachusetts

The development of a prototype lunar transponder for Air Force Cambridge Research Laboratories by General Dynamics/Astronautics demonstrates the feasibility of designing future transponders for hard landings on the moon. Table 1 provides some of the design characteristics of the prototype transponder. Advanced solid-state circuitry, stripline microwave techniques, and special environmental packaging were used in its design [*General Dynamics/Astronautics*, 1963].

Figure 1 shows an expanded view of the prototype I lunar transponder components. On the moon the transponder functions essentially as a frequency-modulated transceiver, which receives a 5052-Mc/s carrier frequency from an earth-based tracking system. The carrier frequency is modulated by a 4-kc/s range measurement signal, which is retransmitted through the same transponder directional antenna on a nominal 5000-Mc/s carrier frequency to the earth-based tracking system. Also, a course modulation frequency of 160 cps is used for ambiguity resolution in the range measurement determination. The voltage-controlled oscillator and the phase detector form a phase-lock loop, which has sufficient bandwidth for retransmission of the range measurement signal.

A continuous wave (CW) ranging technique was selected over a pulse radar technique for the prototype development. *Beach et al.* [1962] made a theoretical analysis of both techniques based on accuracy limitations imposed by thermal noise. Results indicated that the CW carrier was superior, when phase coherent, and compared with equal signal to noise density ratios for both techniques.

An input carrier frequency in the 5000-Mc/s range was selected to minimize tropospheric and ionospheric effects. At a true elevation angle of 15° the tropospheric range error is 9 meters. Standard correction methods can be used to reduce this error to about 1 meter. At frequencies greater than 1000 Mc/s, ray bending due to the ionosphere can be disregarded. Tropospheric ray bending is less than 0.1° for a true elevation angle of 10°. The number of free electrons in the ionosphere depends on numerous variables, such as the sun's activity, the observer's geomagnetic latitude, seasonal changes, and time of day. As a result, accurate corrections to an apparent ray path are difficult. However, at a

TABLE 1. General Design Characteristics of the Prototype I Lunar Transponder

Characteristics	Capabilities
Input frequency	5052 Mc/s
Output frequency	96/97 of phase-locked input frequency
Modulation frequency	4 kc/s, 160 cps
Shock	3000G's in any direction for a duration of 3 msec
Weight (without batteries)	1.8 kg
Volume	1190 cm^3 (12.9 cm × 14.2 cm × 6.5 cm)
Configuration	Rectangular parallelepiped
Controlled operating temperature (inside survival package)	0° to 30°C
Voltage input	25 to 31 volts dc
Power consumption	Not more than 15 watts at 28 volts dc
Output power level	100 milliwatts minimum
Warm-up time	Not more than 1 minute at operating temperature

Optical Radar Using a Corner Reflector on the Moon

C. O. ALLEY,[1] P. L. BENDER,[2] R. H. DICKE,[3] J. E. FALLER,[2] P. A. FRANKEN,[4]
H. H. PLOTKIN,[5] AND D. T. WILKINSON[3]

In a recent letter *Hunt* [1964] described a microwave transponder that can be landed on the moon and that can be used, in conjunction with a modified Glotrac station, to measure the distance between station and landing site. He also suggests several interesting measurements that could be made on the earth-moon system if the range accuracy were sufficiently well developed. The purpose of this letter is to point out the capabilities and possible advantages of an optical radar system which uses a corner reflector on the moon's surface.

Smullin and Fiocco [1962] have demonstrated that laser beams can be scattered from the moon's surface and detected back at the earth; however, the return signals were too weak and too spread out (in time) to be used for precision ranging. *Hoffman et al* [1960] have pointed out the advantages of using corner reflectors on an artificial satellite to permit precision tracking. More recently, *Plotkin* [1964] has described an optical radar system that is capable of making precision range measurements to satellites which have been equipped with corner reflectors.

A typical optical radar system is shown schematically in Figure 1. The laser beam (pulsed or continuous wave) is sent through a transmitting telescope which tracks the corner reflector on the moon's surface. A small part of the reflected light is collected by the receiving telescope, which also tracks the reflector. (If a single telescope with a T/R switch is used, there is some sacrifice of received intensity owing to velocity abberation.) The correlator measures the light travel time to the reflector and back. The efficiency of such a system, that is, the ratio of the number of received to the number of transmitted photons, is given approximately by

$$\eta = \frac{1}{4}\,\frac{A^2 D_T^2 D_R^2}{r^4 \theta^2 \lambda^2 D_L^2}\, T_a^2 T_o$$

where

A is effective area of the corner reflector, ≈ 150 cm^2.
r is range to the corner reflector, $\approx 3.7 \times 10^{10}$ cm.
λ is wavelength of laser light, $\approx 7 \times 10^{-5}$ cm.
θ is angular radius of laser beam divergence, $\approx 10^{-5}$ rad.
D_R is diameter of receiving telescope, ≈ 100 cm.
D_T is diameter of transmitting telescope, ≈ 100 cm.
D_L is diameter of laser rod, ≈ 2 cm.
T_a is transmission through the atmosphere, $\approx 85\%$.
T_o is transmission through optical elements, $\approx 30\%$.

For a system having the parameters given above, the efficiency is $\approx 3.3 \times 10^{-14}$; thus, we see the need for a high power laser as the light source. The expected return from the corner reflector is some 100 times stronger than that due to diffuse scattering by the lunar surface.

For pulsed radar applications, a *Q*-switched ruby laser can be used as the light source. The parameters used above for estimating η are typical of a system employing a ruby laser which is available commercially and is capable of delivering 10^{18} photons in a pulse of 10^{-8} second duration. With this laser as the light source and with a detector of 3% quantum efficiency, we estimate a return signal of 1 photoelectron per transmitted pulse. Therefore, the probability of getting a return signal from a given trans-

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[2] Joint Institute for Laboratory Astrophysics, Boulder, Colorado.

[3] Palmer Physical Laboratory, Princeton University, Princeton, New Jersey.

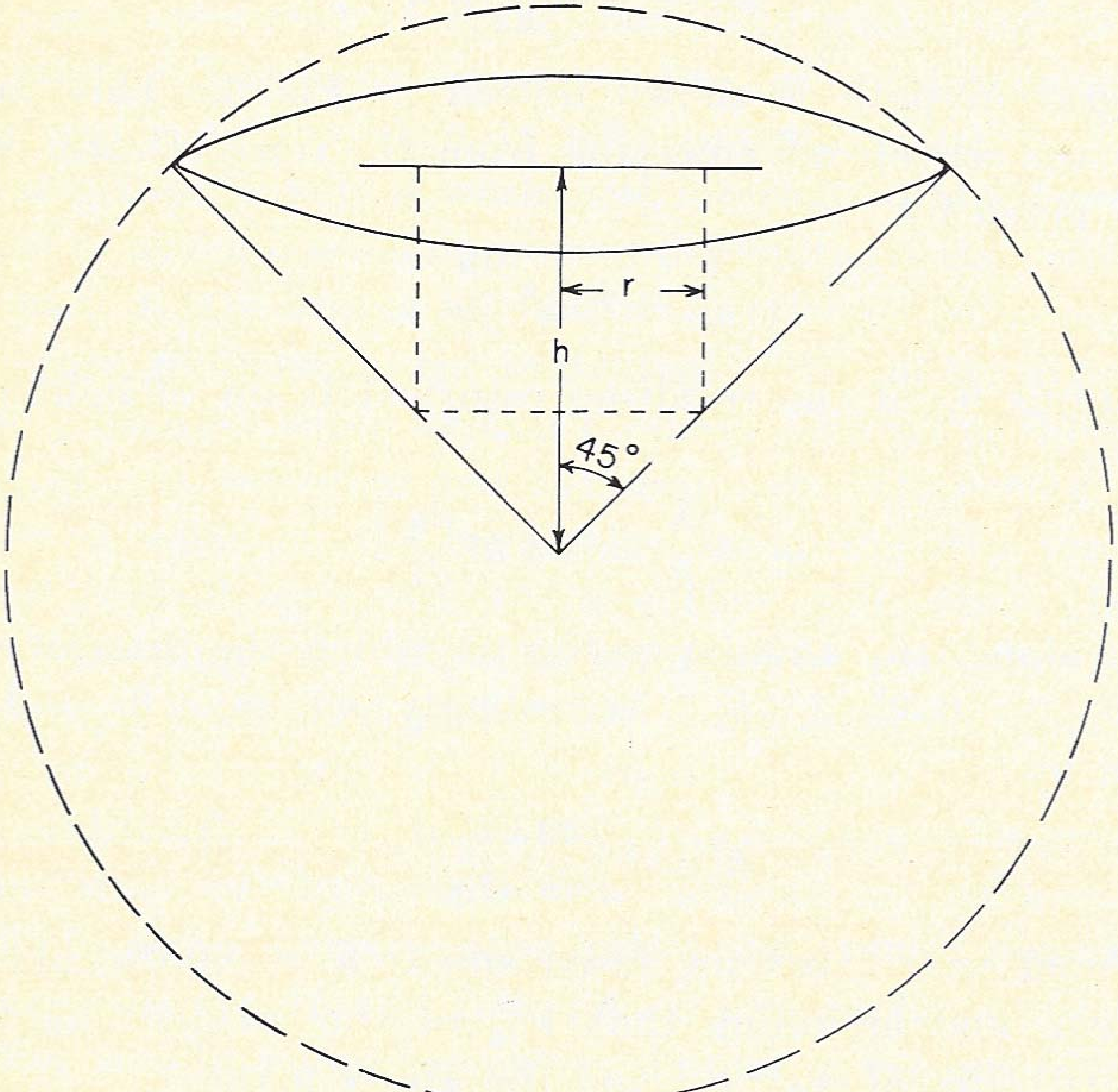
[4] Department of Physics, University of Michigan, Ann Arbor, Michigan.

[5] Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland.

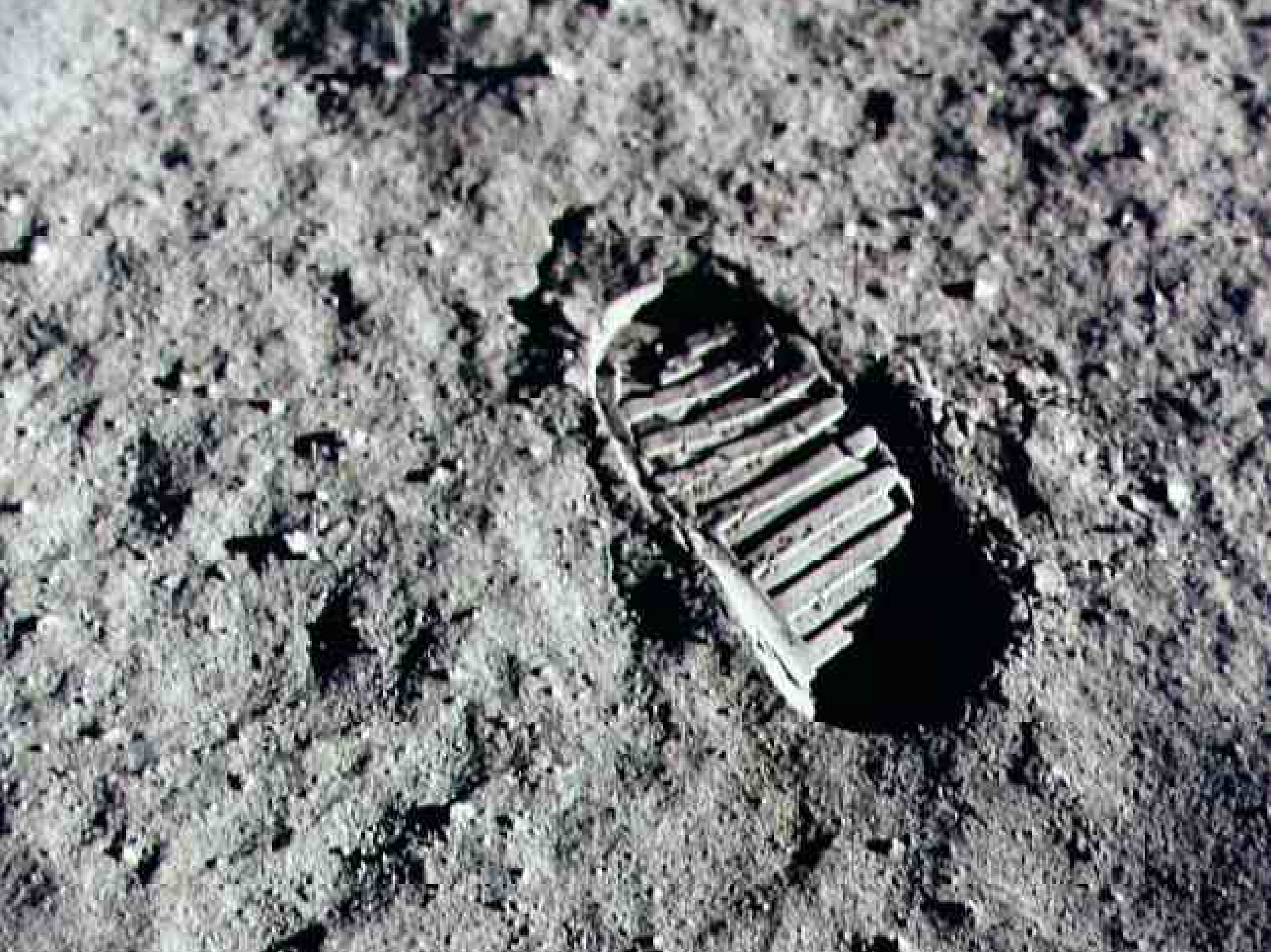
LURE (Lunar Ranging Experiment) Team Created

The Lunar Laser Ranging effort was proposed as an Apollo experiment in 1965.

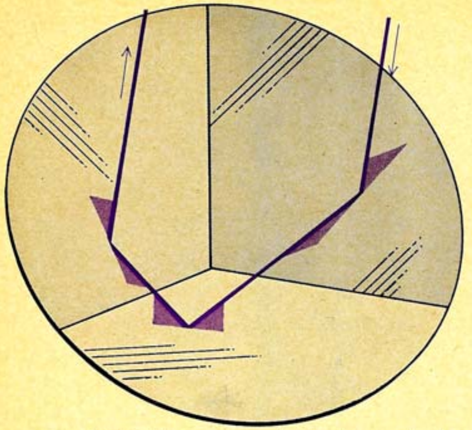
- The array must be fabricated of space-approved materials, and, as a design goal, should have a ten-year life in the lunar environment.


r
h
45°

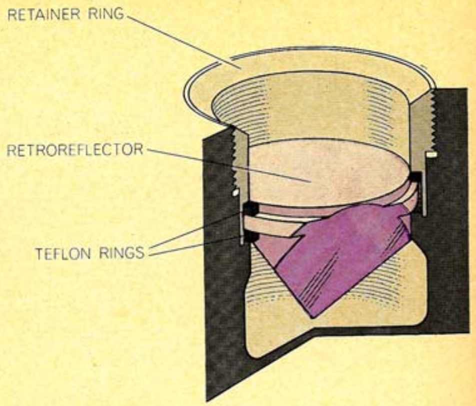
Because of NASA’s interest in including a astronaut-undemanding and passive experiment in the Apollo 11 scientific payload, the Lunar Ranging Experiment was accepted.



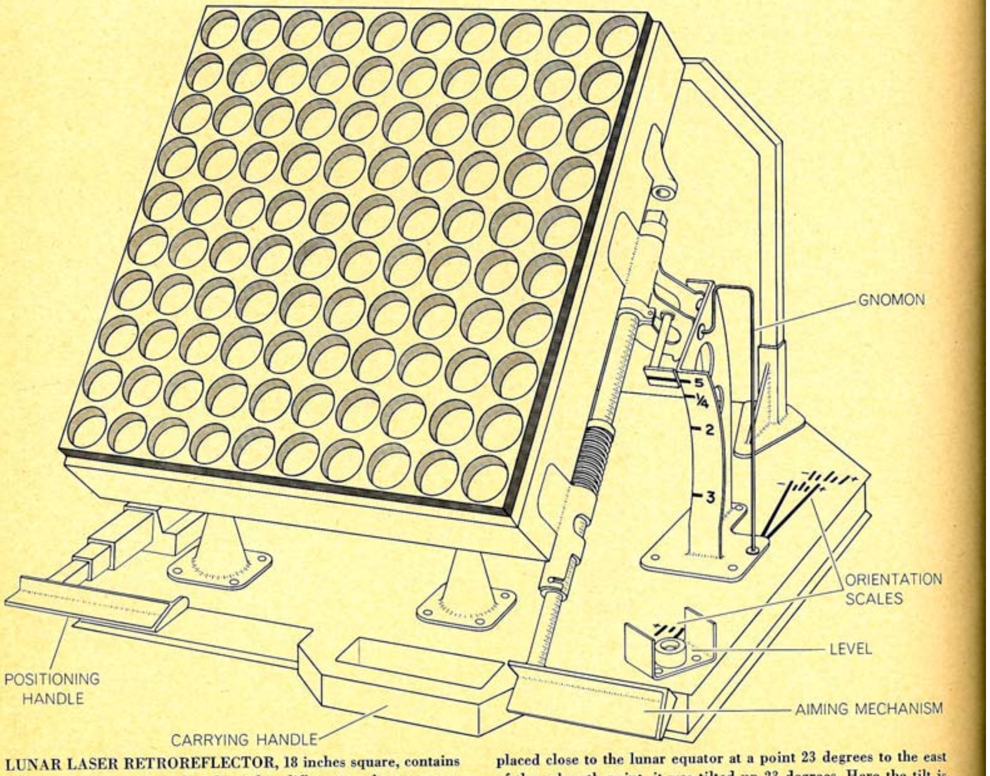

WESLEYAN
UNIVERSITY



CORNER REFLECTOR, or corner cube, has the property of returning a ray of light (*color*) on a path exactly parallel to that of the incident ray. At each internal surface the angle of reflection equals the angle of incidence, as indicated by the colored triangles. The corner reflectors that were used in the array placed on the moon were cut from accurately polished cubes of fused silica.

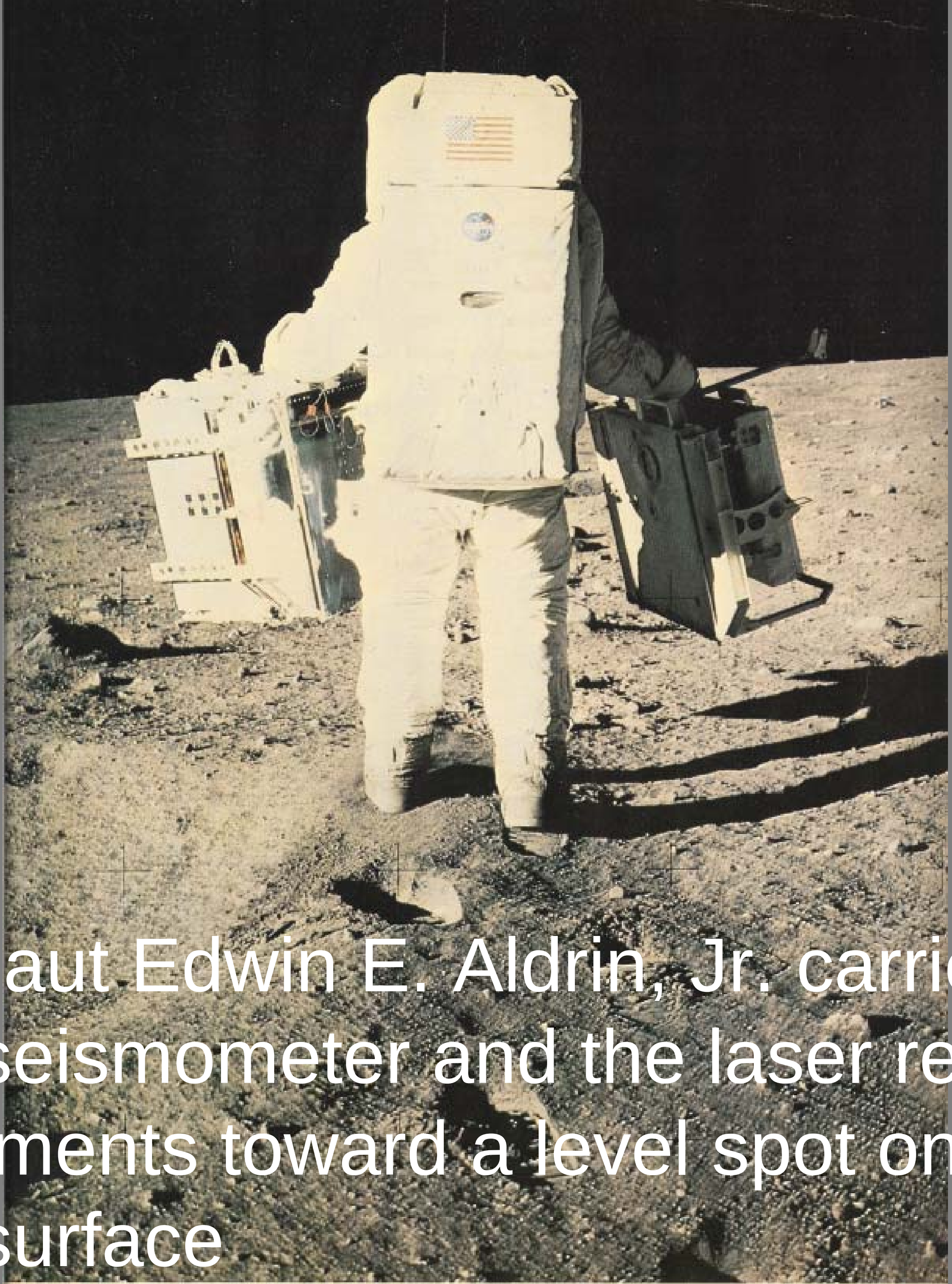


MOUNTING FOR CORNER CUBE was designed by Arthur D. Little, Inc., to withstand the vibration and acceleration of an Apollo lift-off and, once on the moon, to minimize thermal gradients that would affect the optical performance of the reflectors. Each corner reflector is recessed by about half its 1½-inch diameter and is held by Teflon rings in a housing machined from aluminum.

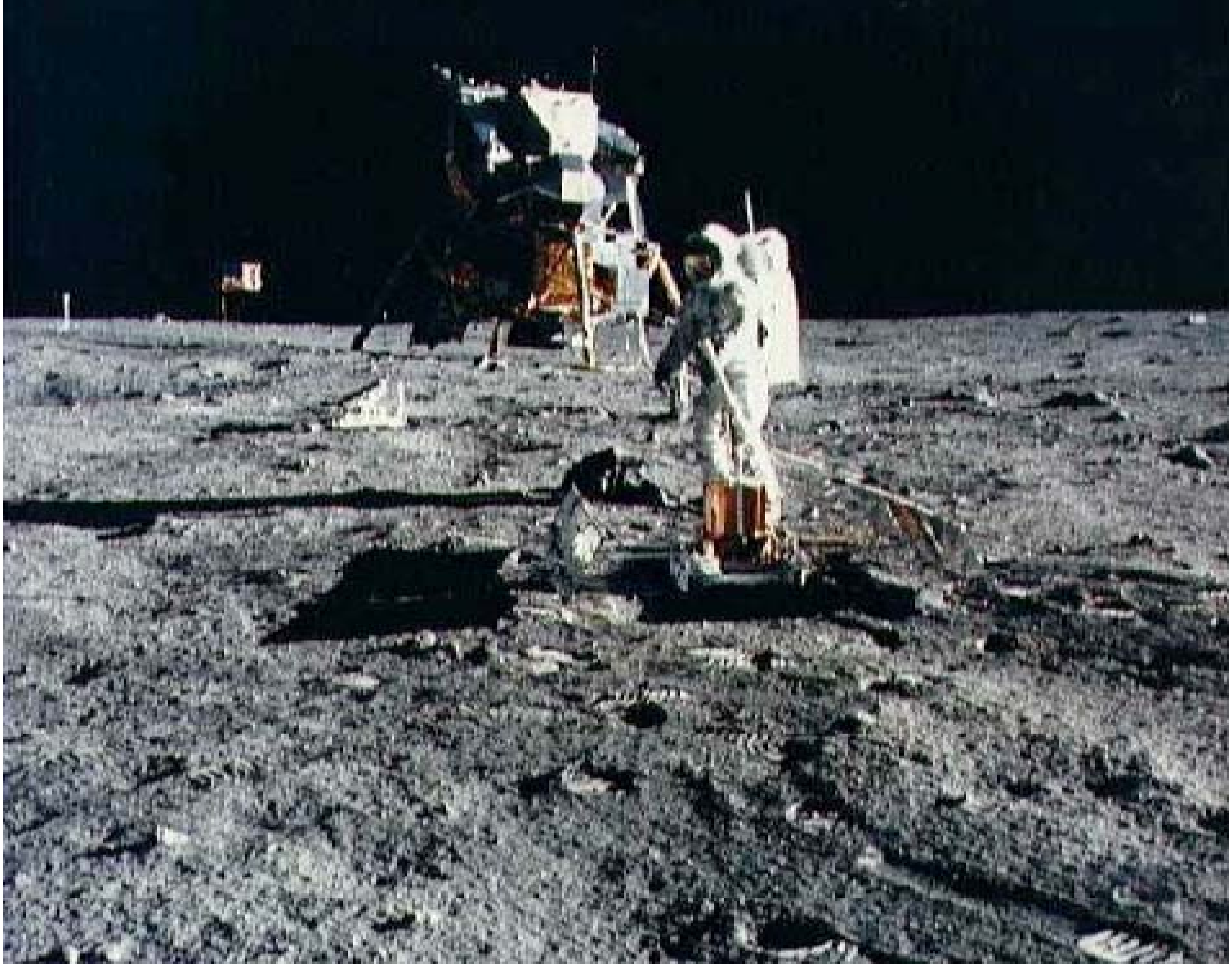


LUNAR LASER RETROREFLECTOR, 18 inches square, contains 100 corner cubes and can be adjusted to different angles to accommodate to different locations on the moon. Since it was actually placed close to the lunar equator at a point 23 degrees to the east of the subearth point, it was tilted up 23 degrees. Here the tilt is greater. The shadow of the gnomon provides east-west orientation.

Apollo 11, July 21,1969

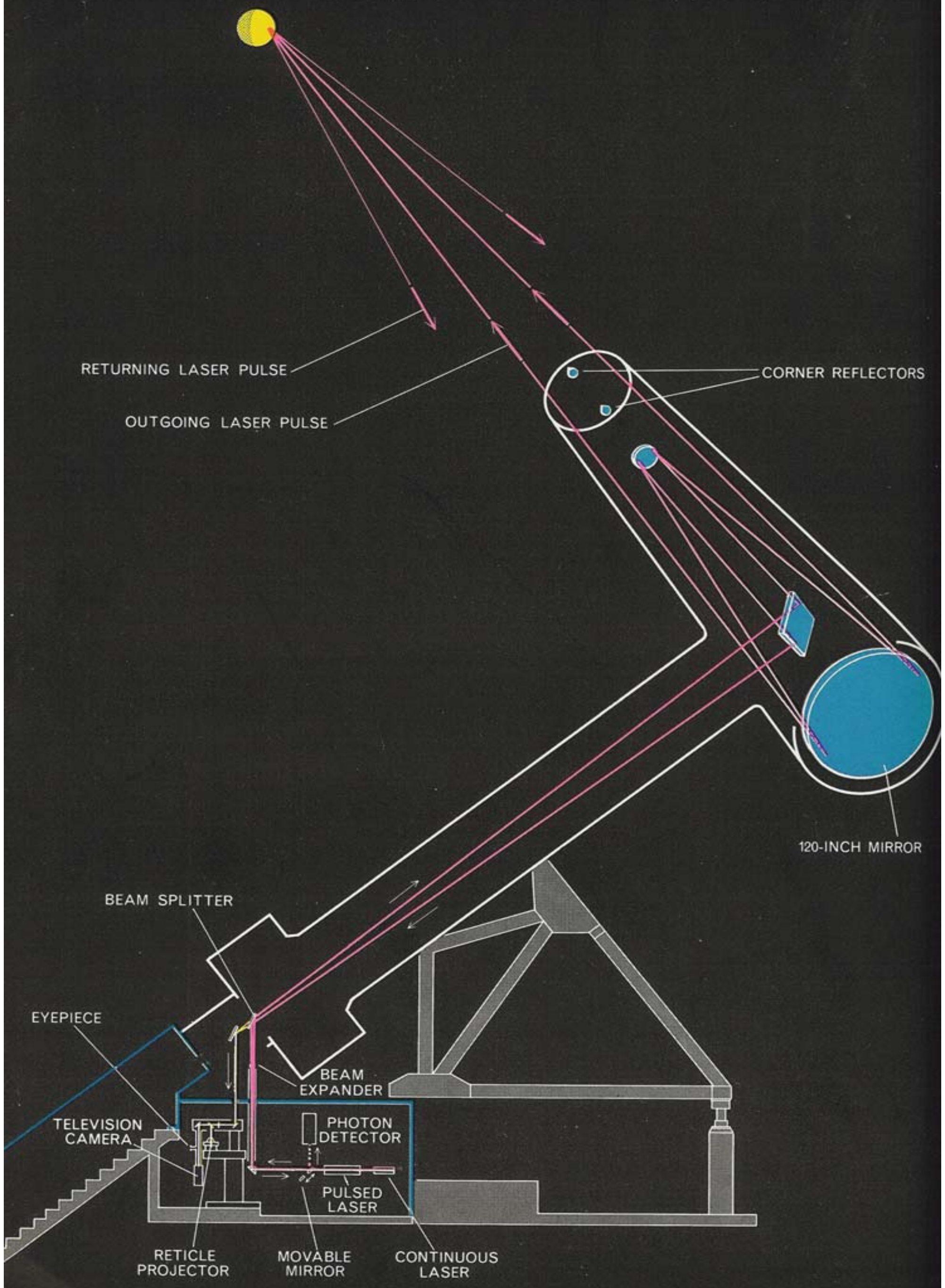


Astronaut Edwin E. Aldrin, Jr. carries the lunar seismometer and the laser reflector experiments toward a level spot on the lunar surface

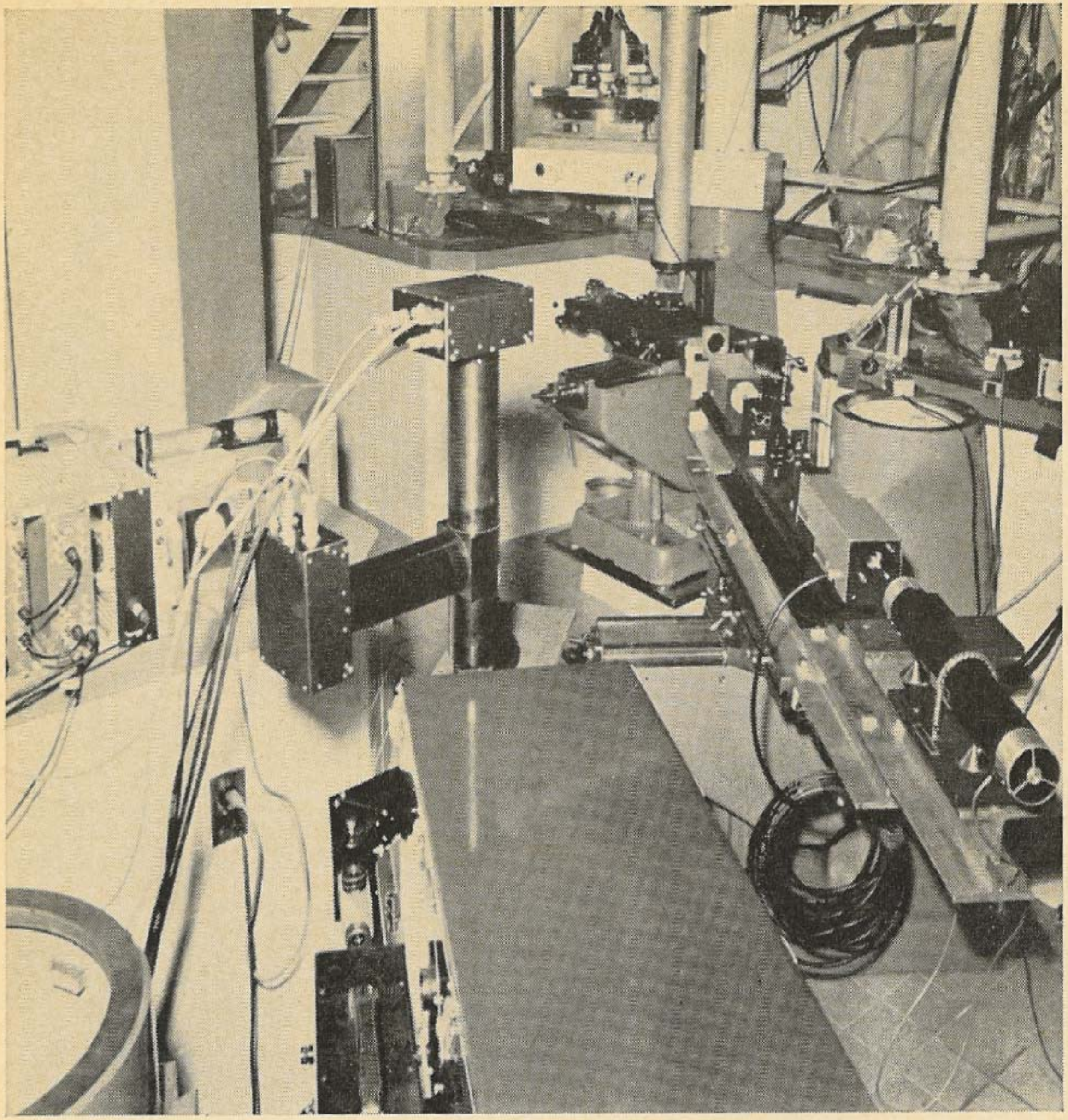


Lunar Laser Ranging

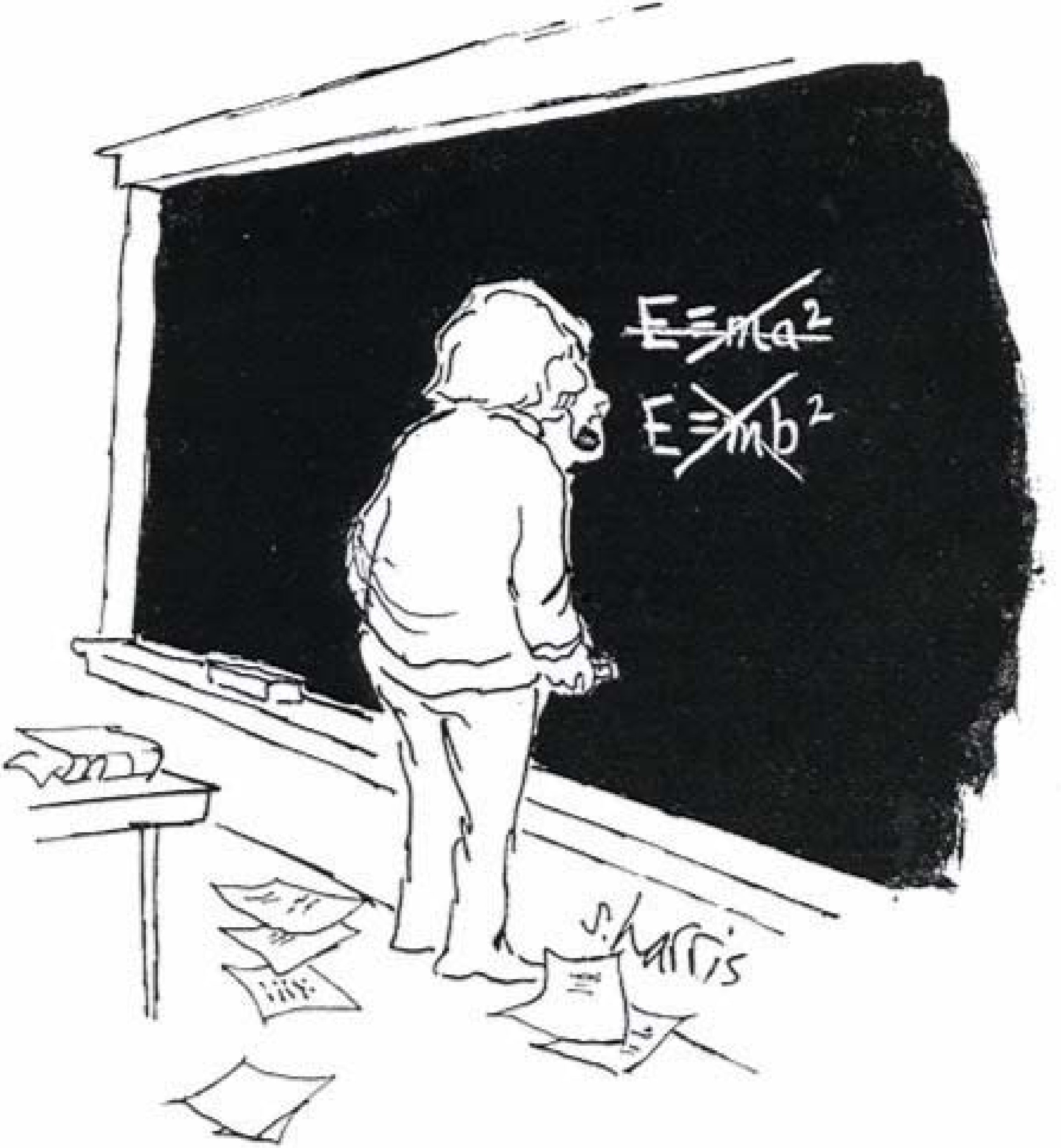
- Laser pulses are sent from stations on the Earth towards the Moon where they hit retroreflector arrays and return to the Earth.
- Ranging started in 1969 and continues to present

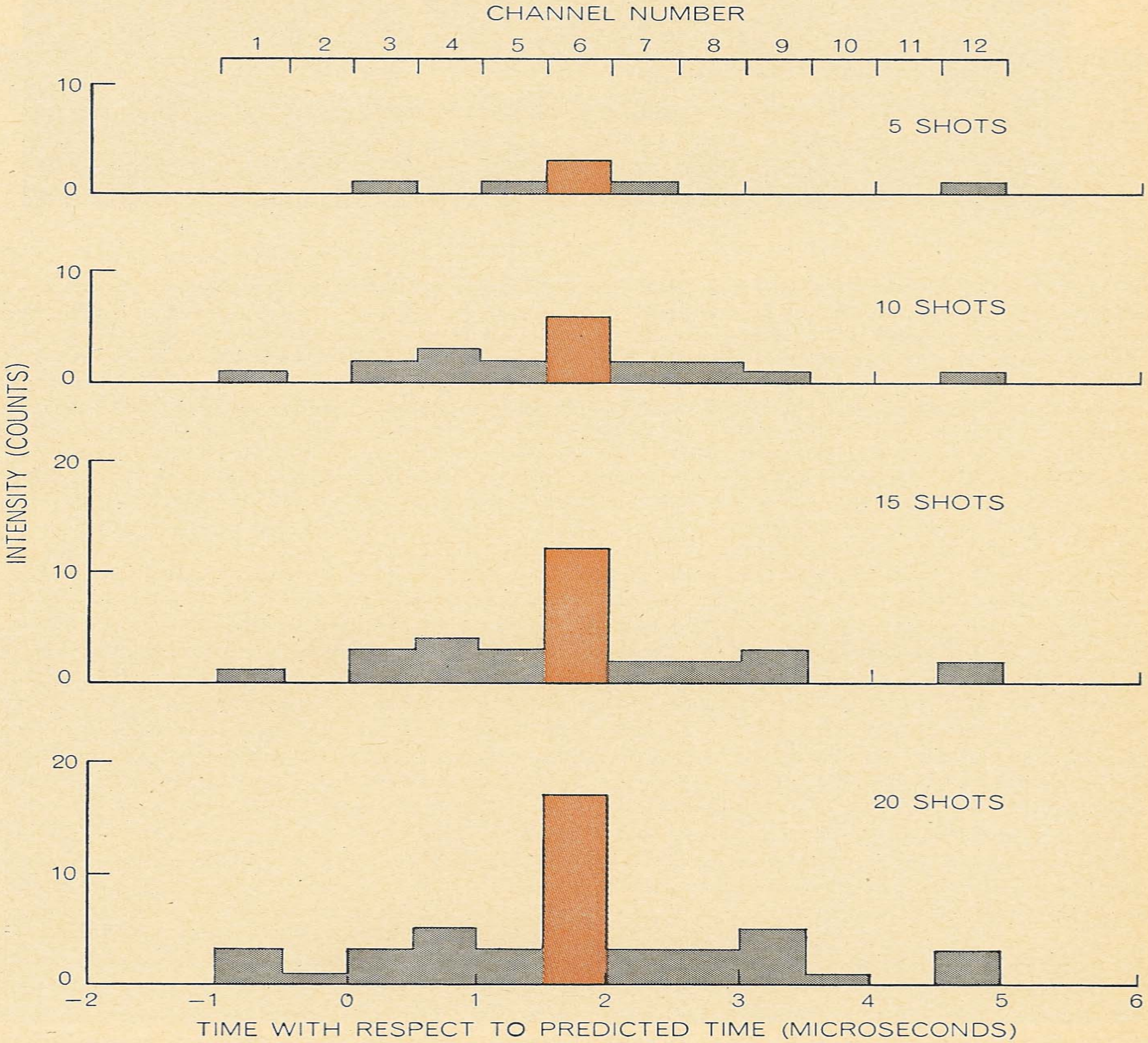


RETURNING LASER PULSE
OUTGOING LASER PULSE
CORNER REFLECTORS
120-INCH MIRROR
BEAM SPLITTER
EYEPIECE
BEAM EXPANDER
TELEVISION CAMERA
PHOTON DETECTOR
PULSED LASER
RETICLE PROJECTOR
MOVABLE MIRROR
CONTINUOUS LASER

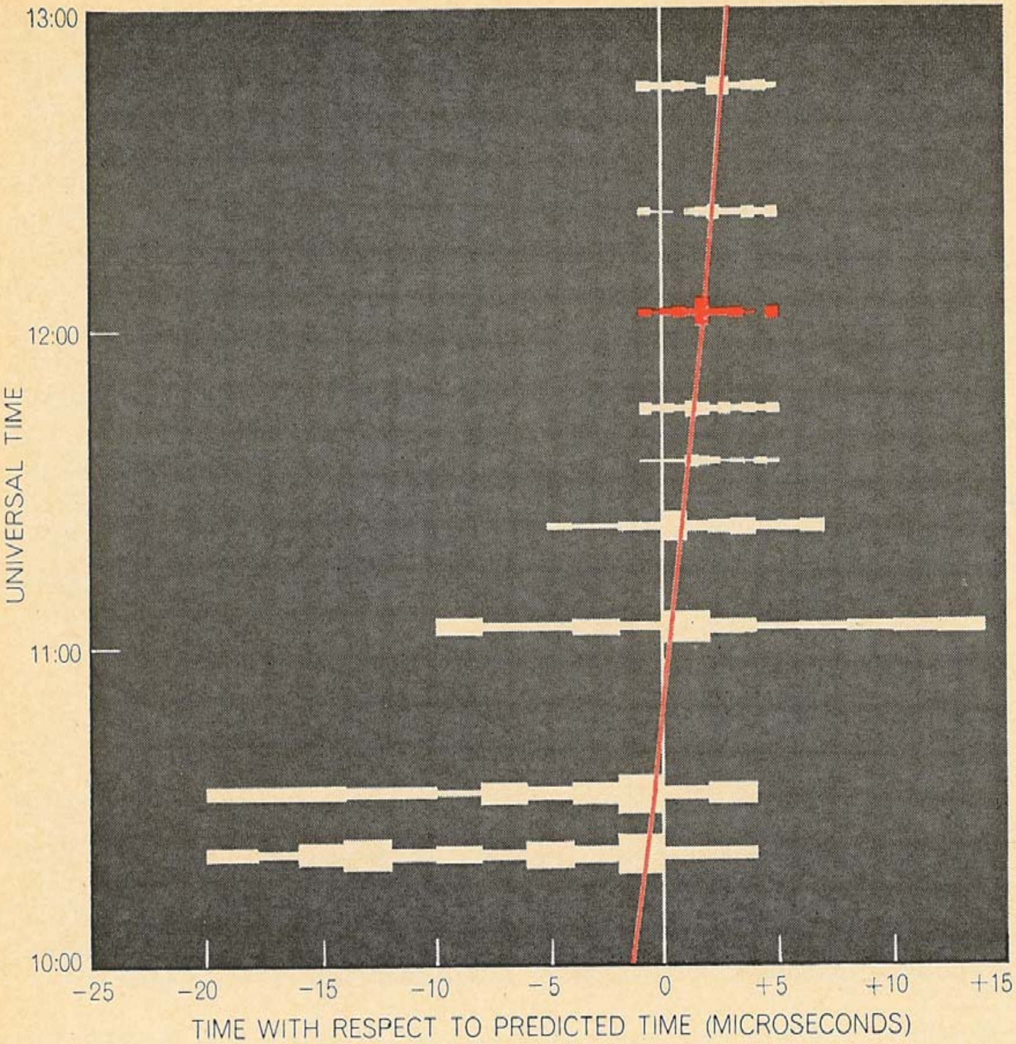


EXPERIMENTAL AREA in a basement room below the 120-inch Lick telescope contained two laser systems, the guidance system for pointing the laser beam at the landing site on the moon and the equipment for detecting the weak return pulse (*see diagram below*).

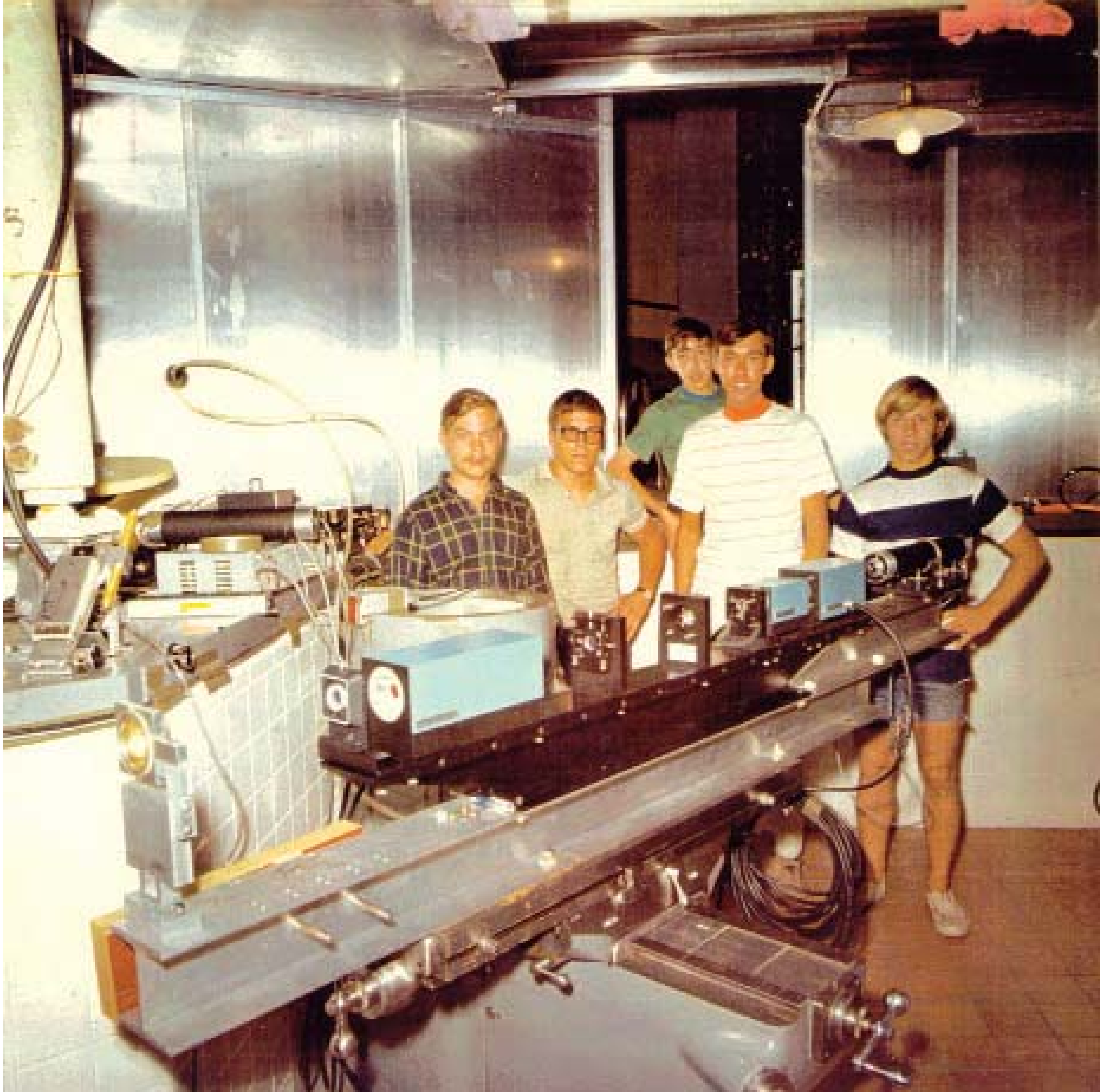

~~$E=ma^2$~~
$\cancel{E=mb^2}$
S. Harris



IDENTIFICATION OF REFLECTED LASER SIGNAL was done by dividing the output of the photon detector into 12 time channels embracing the predicted time of arrival, and observing whether or not one of the channels filled up faster than the others. The width of each channel could be varied from .25 microsecond to four microseconds. On the run shown here, made on August 1, 1969, at the Lick Observatory, the width of each channel was .5 microsecond. One channel, No. 6, filled more rapidly than the others, confirming that the returning photons were indeed coming from the retroreflector array on the moon.

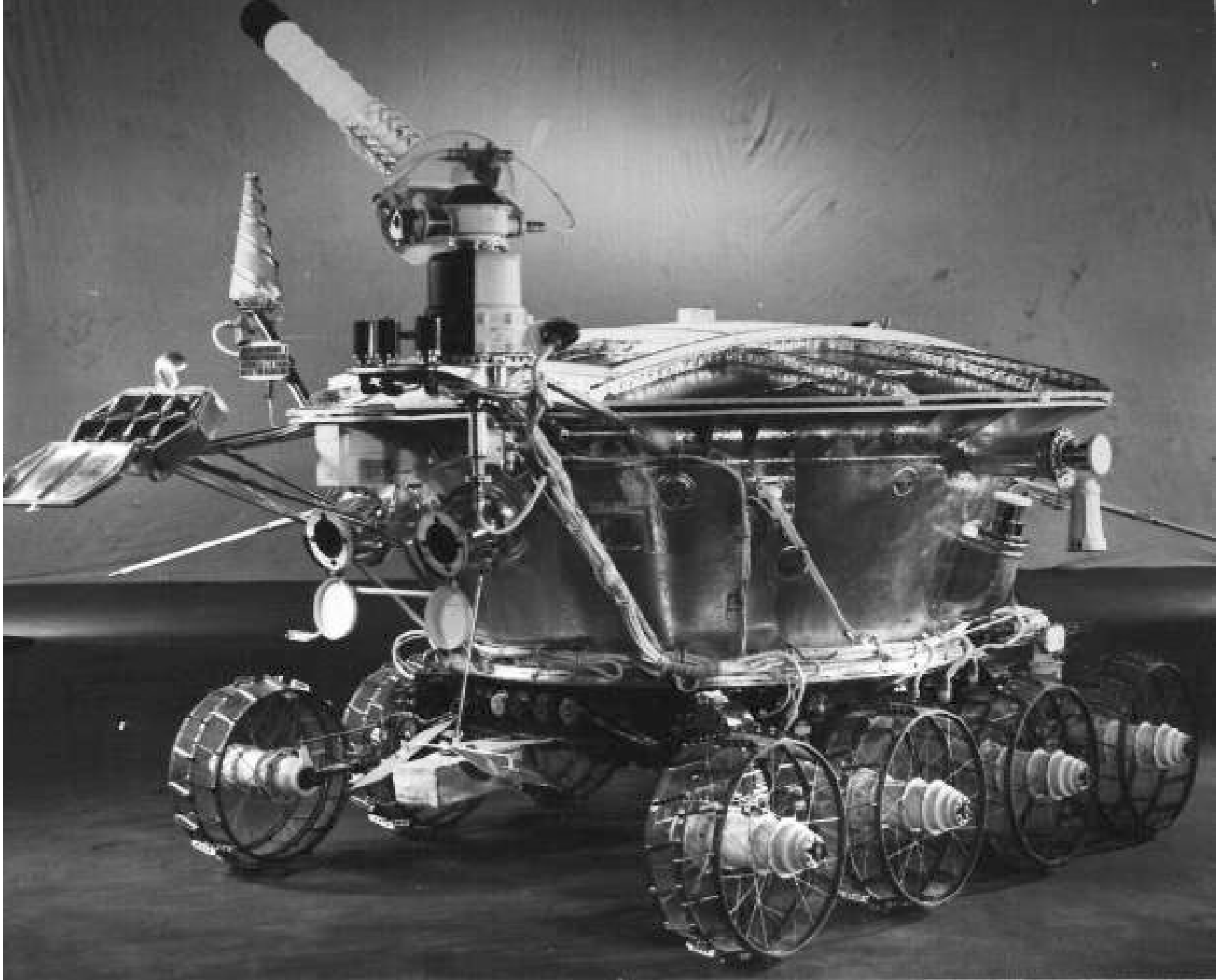


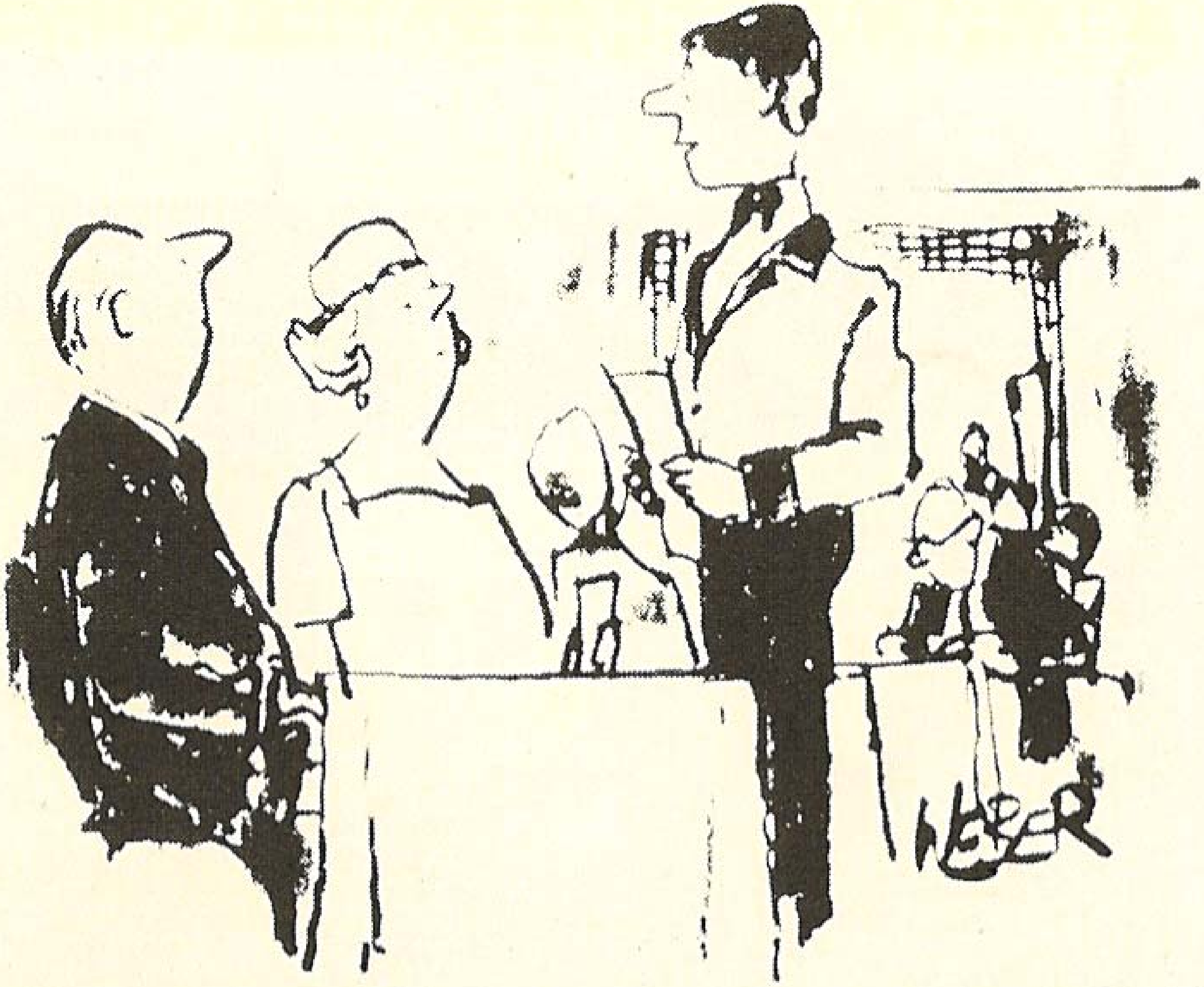
DEPARTURE FROM PREDICTED ARRIVAL TIME presented a puzzle during the lunar-ranging runs made on August 1, the night return pulses from the retroreflector were first detected. Each horizontal bar represents a separate run; the thickness of each segment indicates the number of counts in each of 12 counting channels. The run illustrated on the preceding page, made at 12:03 Universal Time, is shown in color. The colored line drawn through the channels with the most counts indicates that the actual time of arrival of return pulses was at first earlier than the predicted time (*vertical white line*) and then fell behind by more than two microseconds. It was discovered that the 120-inch Lick telescope is actually some distance (about 1,800 feet) from the position used for calculating the range predictions. When the correct location is used, the predicted and actual arrival times agree.



Lunokhod 1, November 1970

[Luna 17]

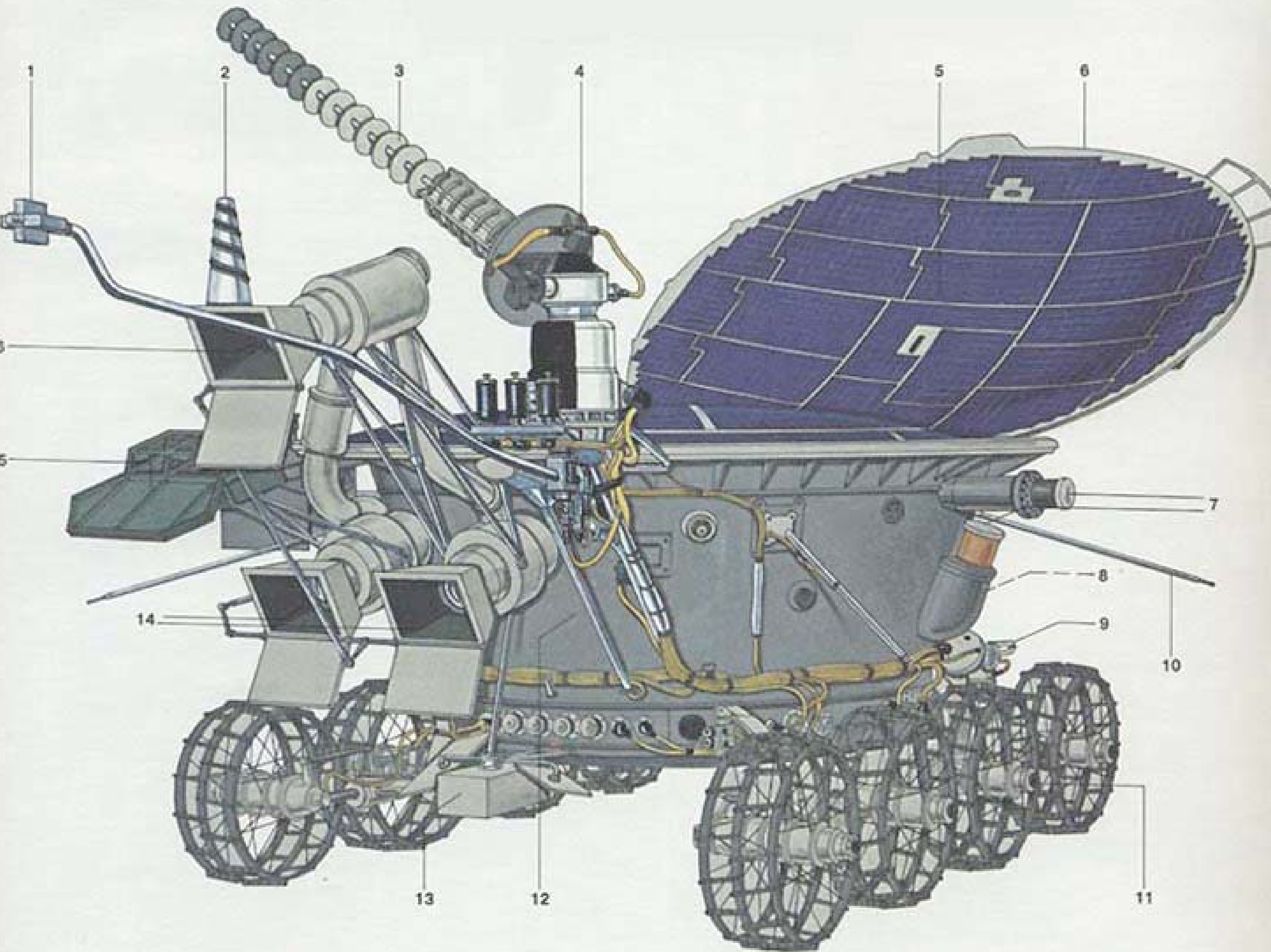




"Good evening. I'm George Graham, Harvard '71. I have an A.B. cum laude in physics, and I can recommend the roast duck unreservedly."

Lunokhod 2, January 1973

[Luna 21]


1
2
3
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5
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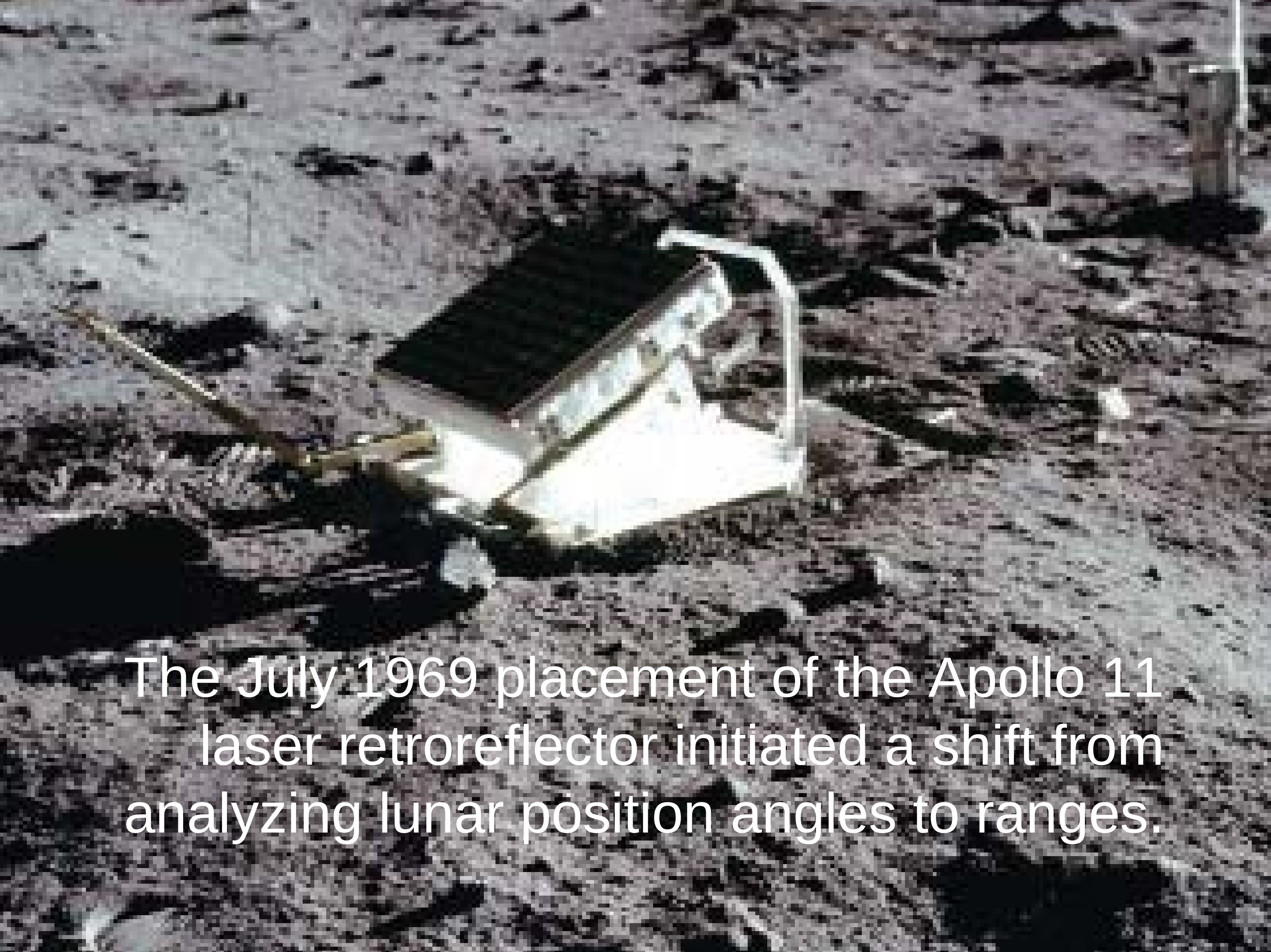
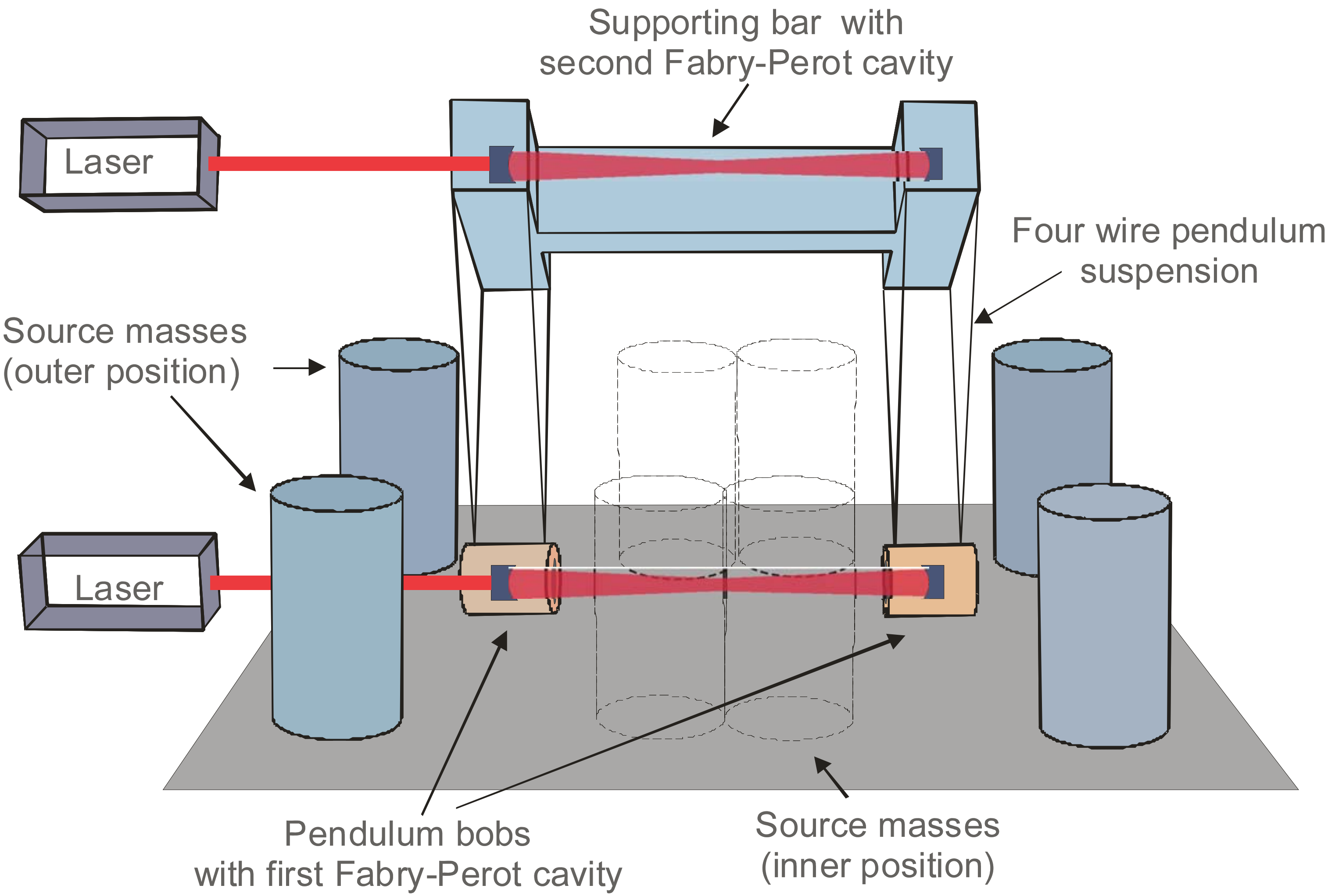
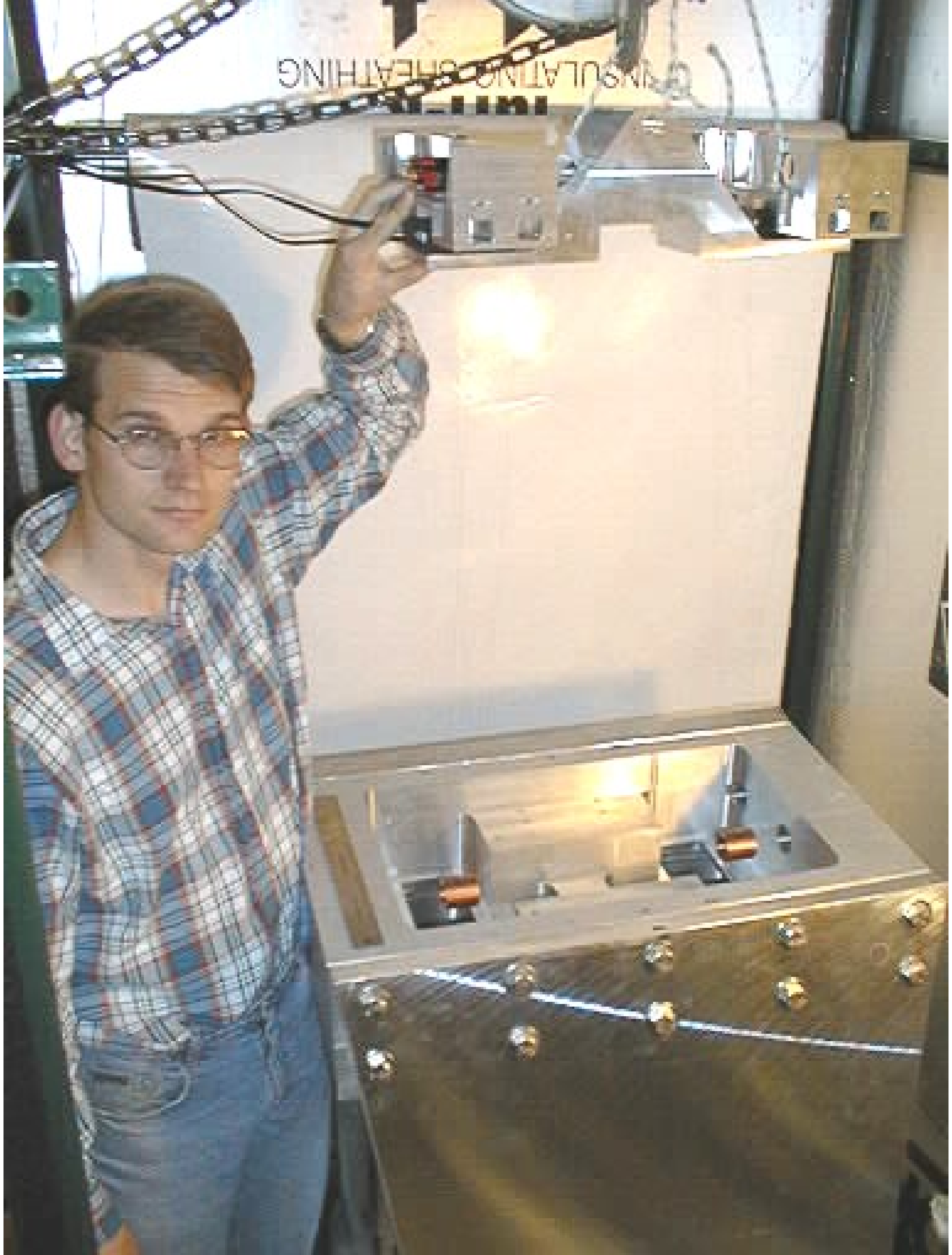
12
11



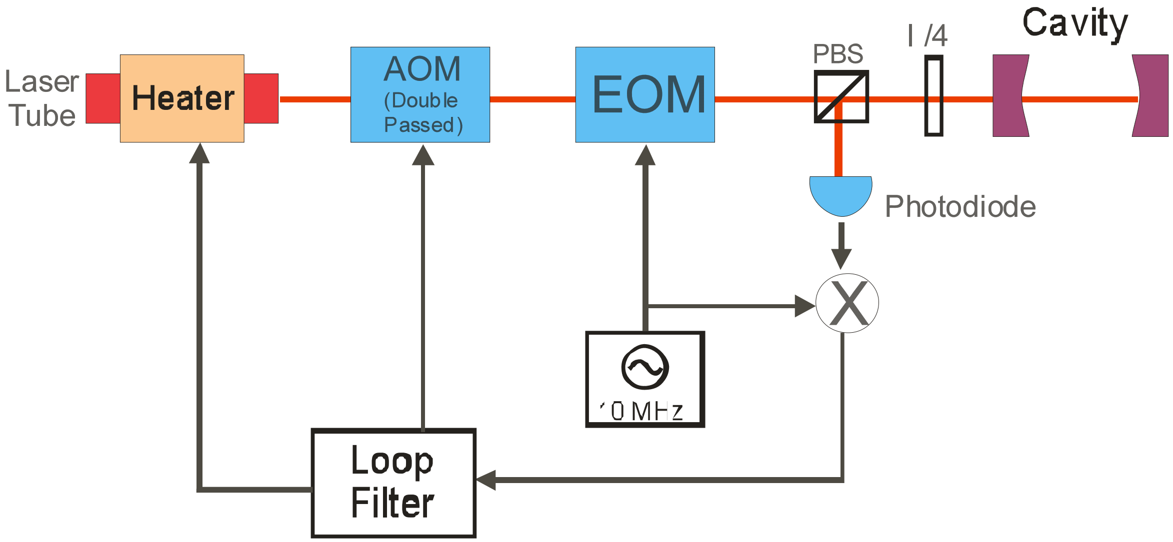
The July 1969 placement of the Apollo 11 laser retroreflector initiated a shift from analyzing lunar position angles to ranges.

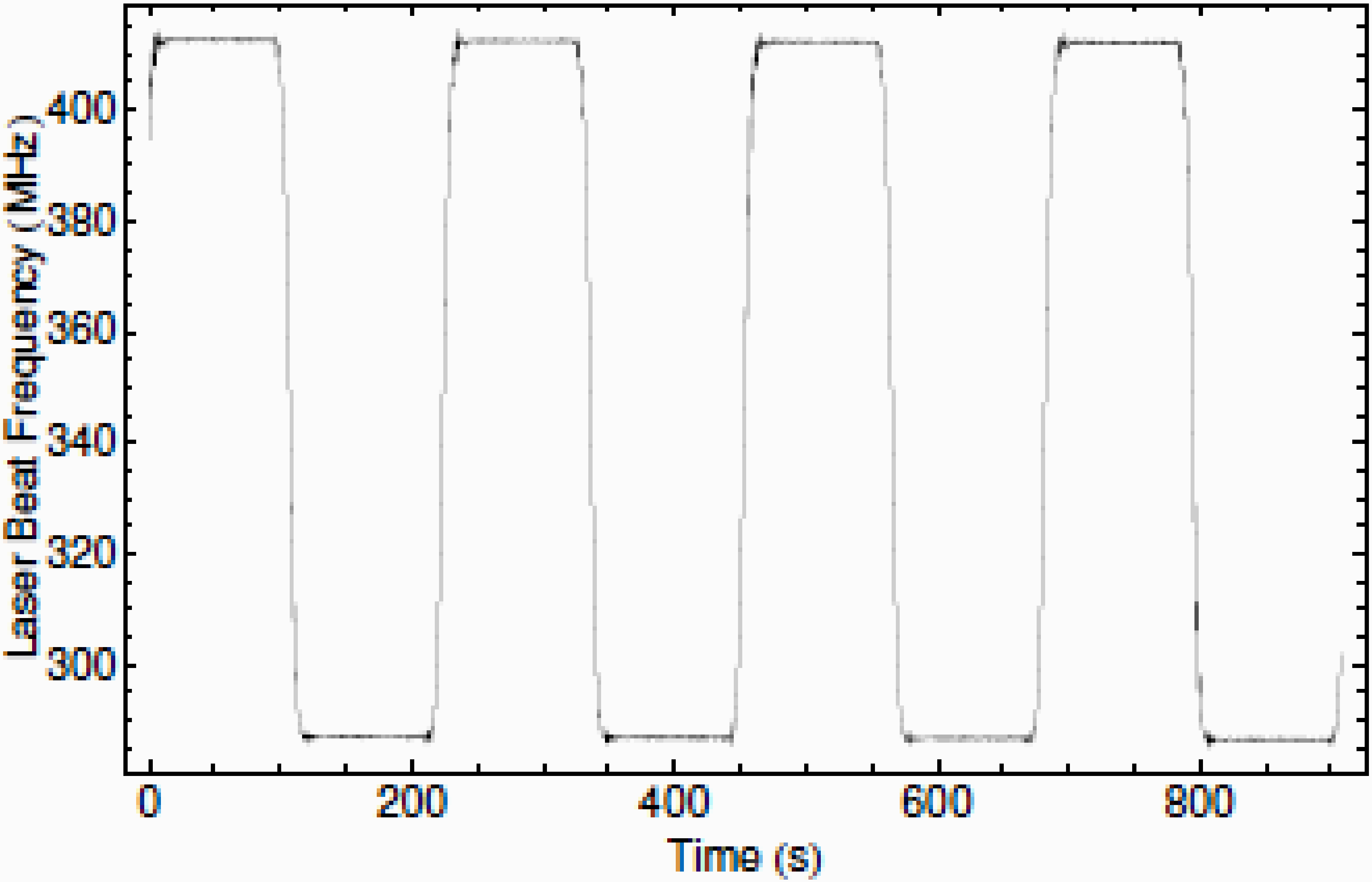
JILA G Experiment




INSULATING SHEATHING

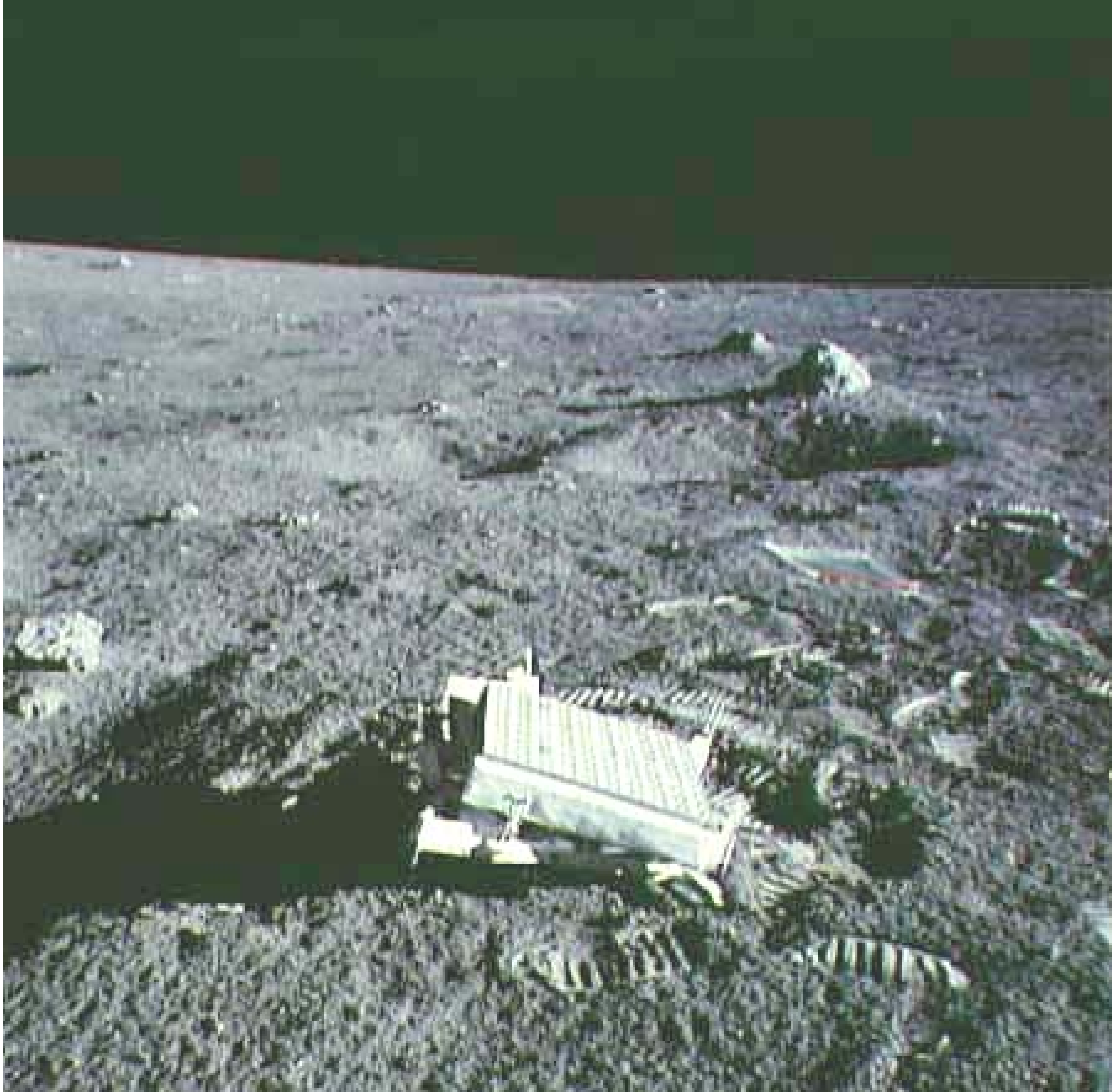
Laser System

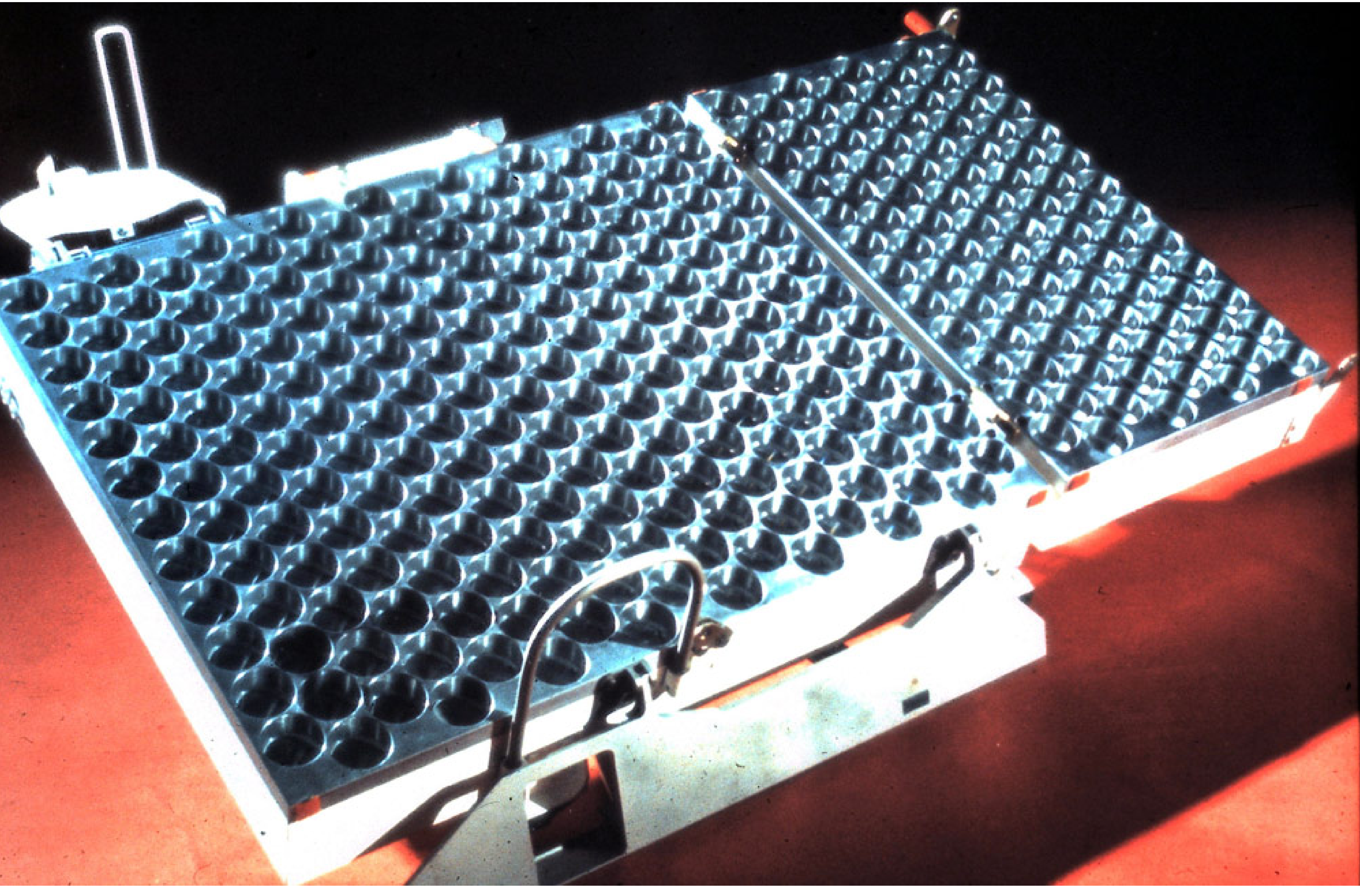

Laser Tube
Heater
AOM
(Double Passed)
EOM
PBS
l /4
Cavity
Photodiode
X
10 MHz
Loop Filter



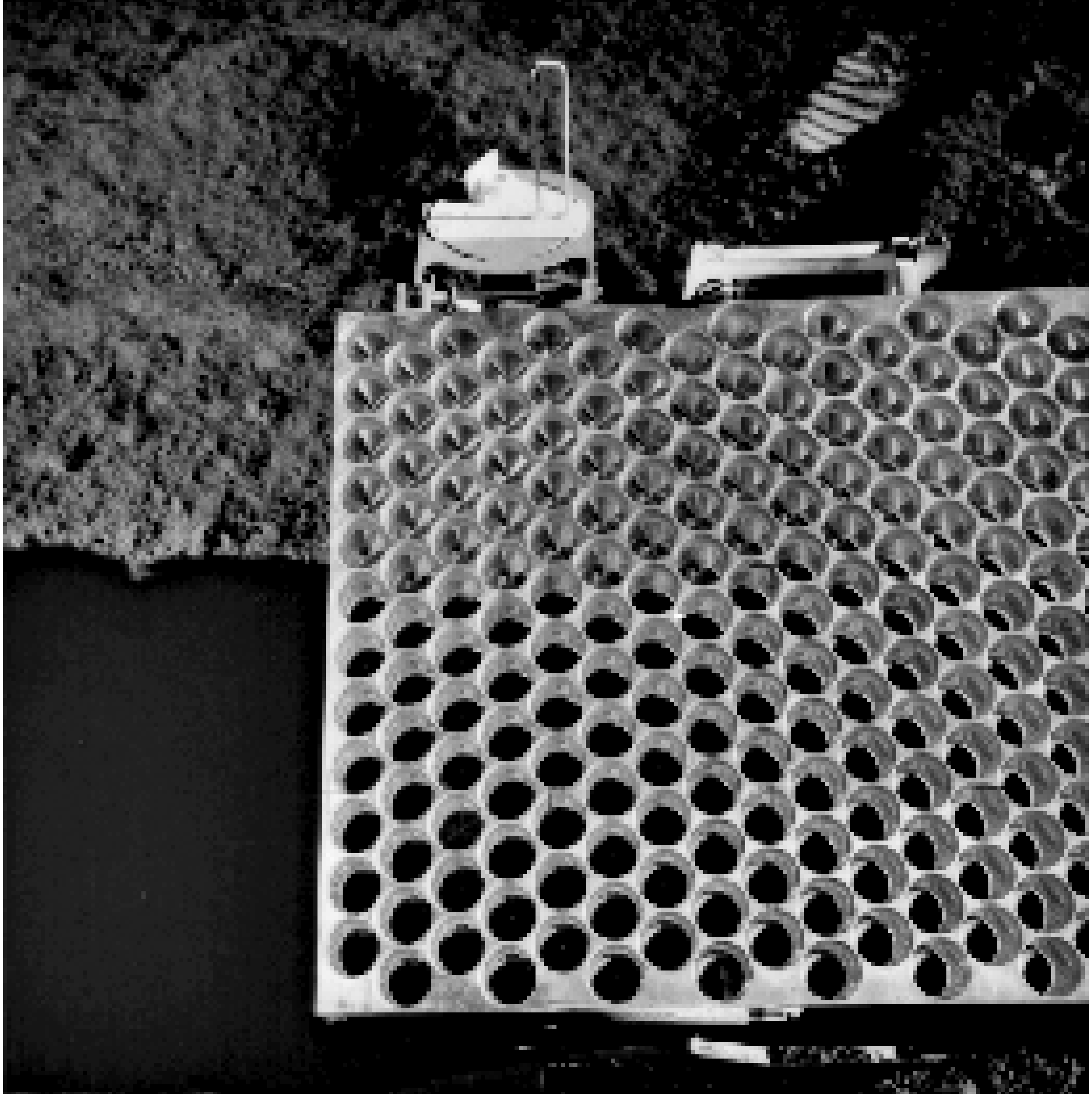
Laser Beat Frequency (MHz)
400
380
360
340
320
300
0
200
400
600
800
Time (s)

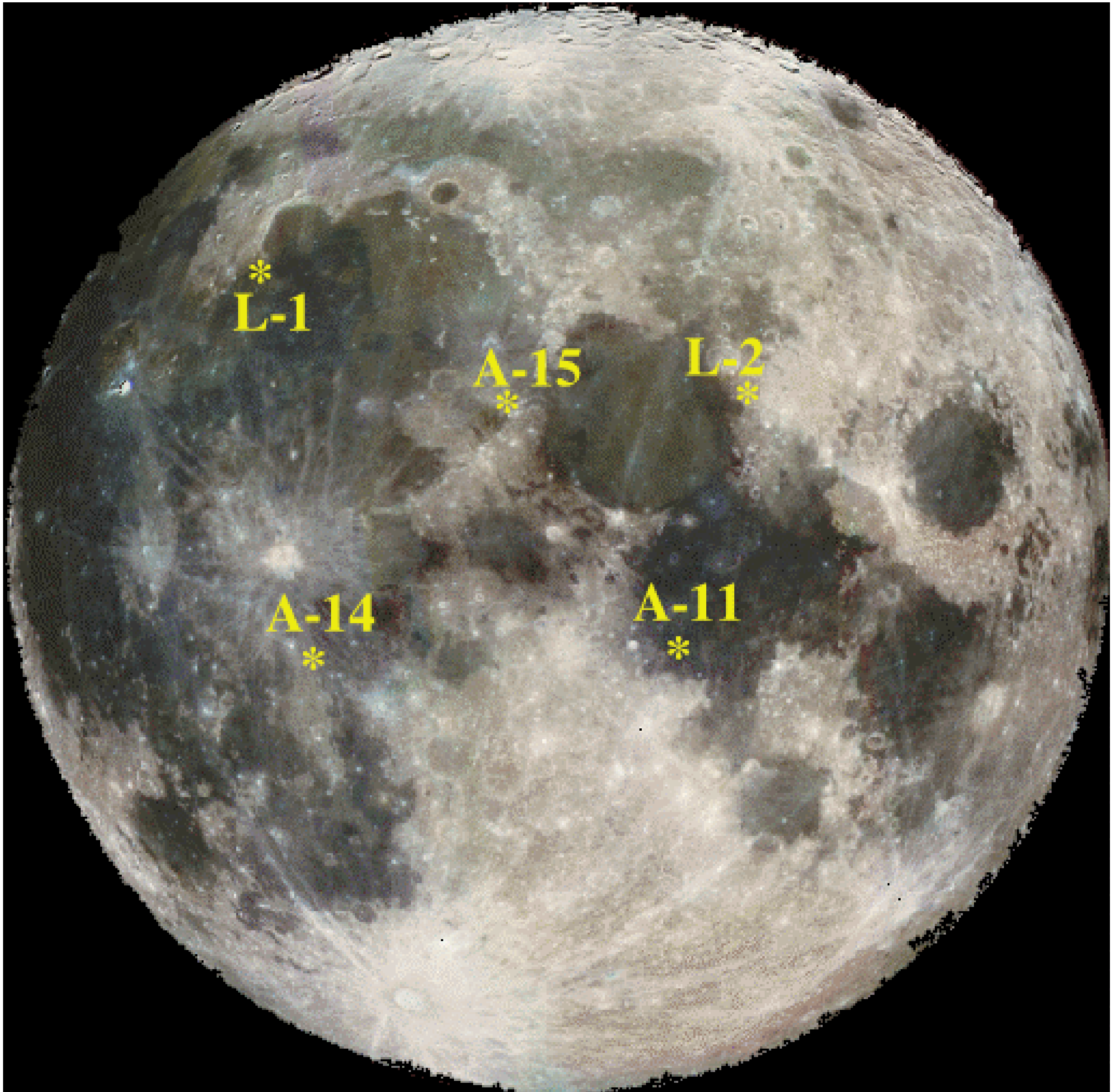
Apollo 14 February 5,1971



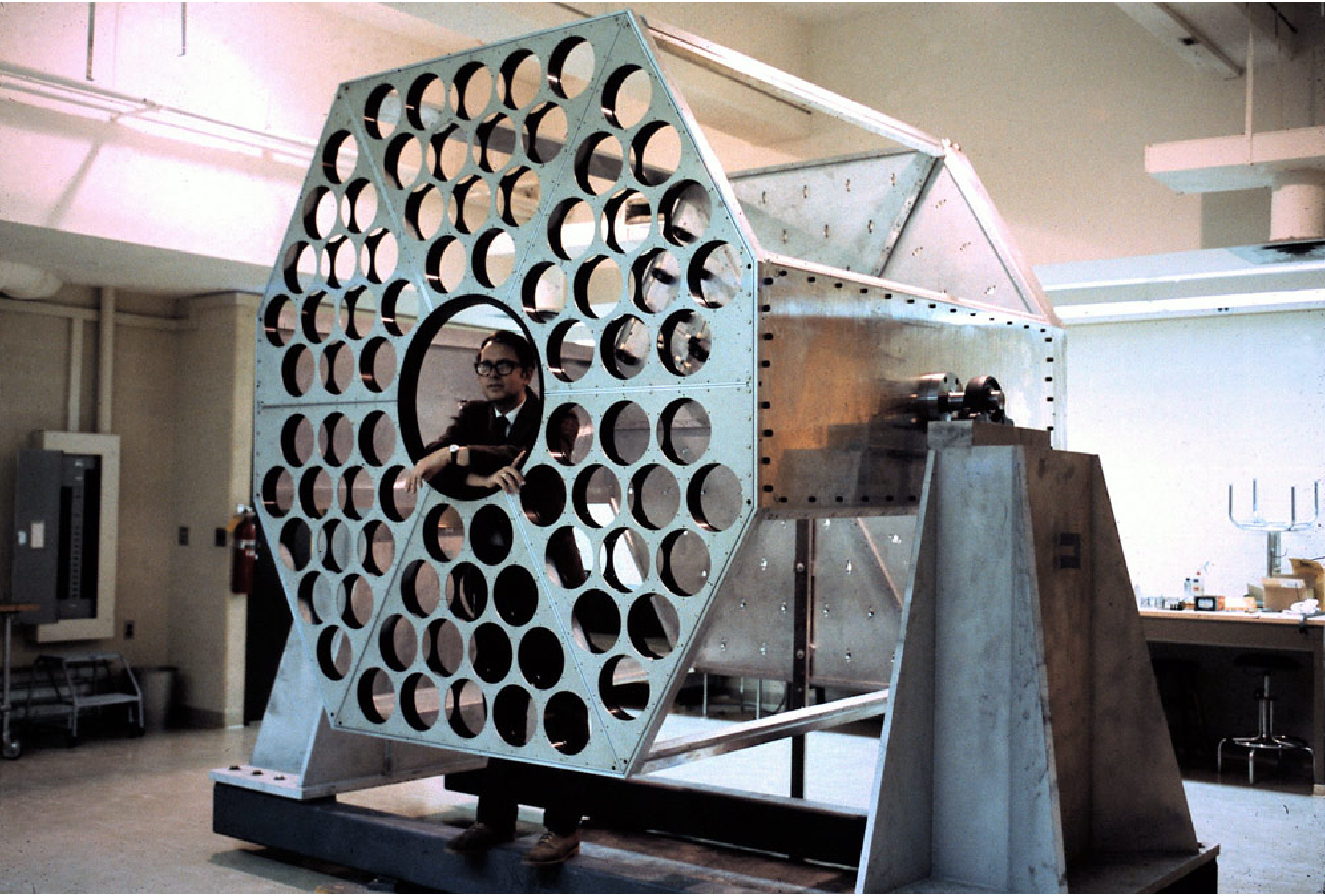


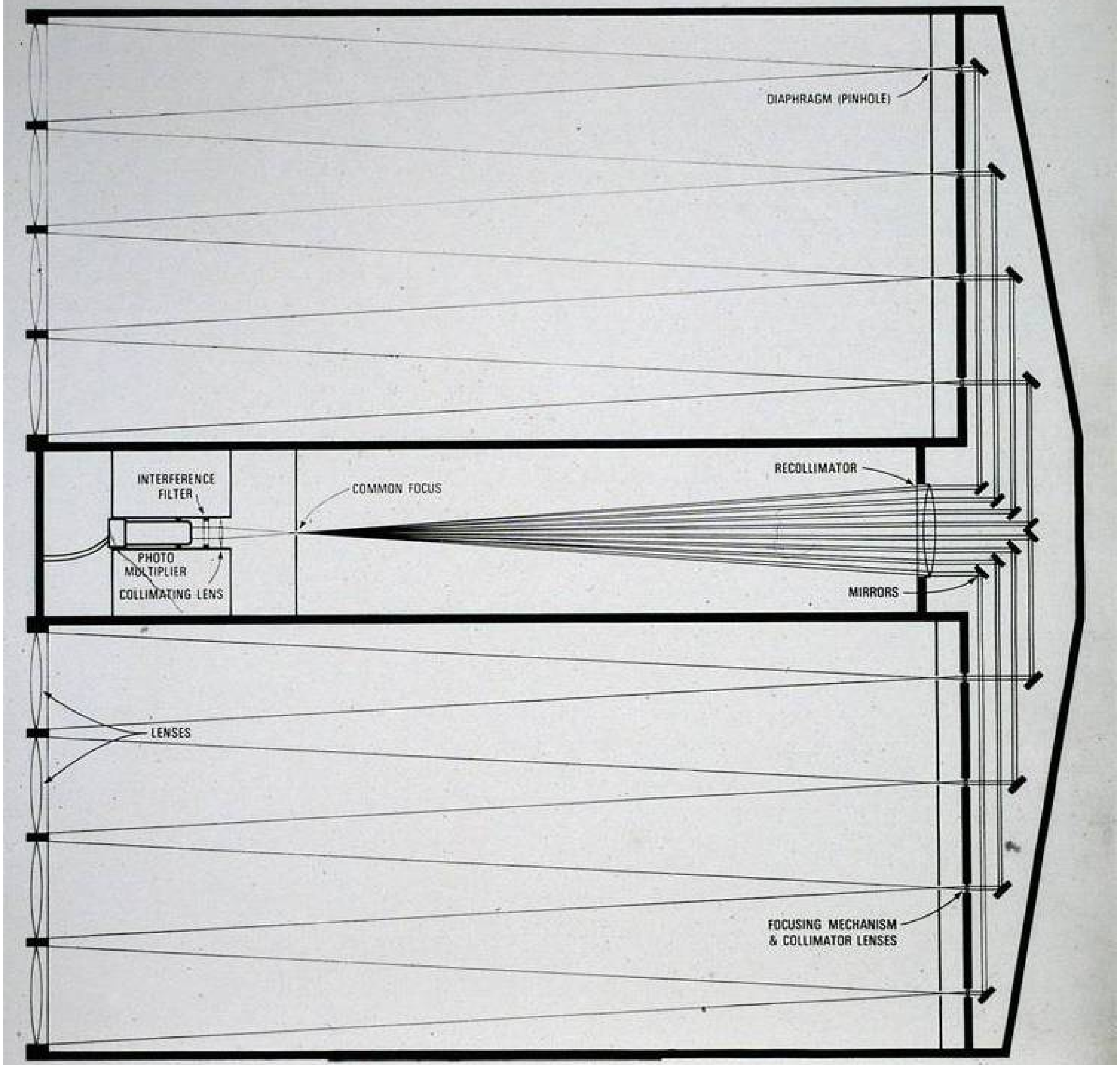
Apollo 15, July 31, 1971

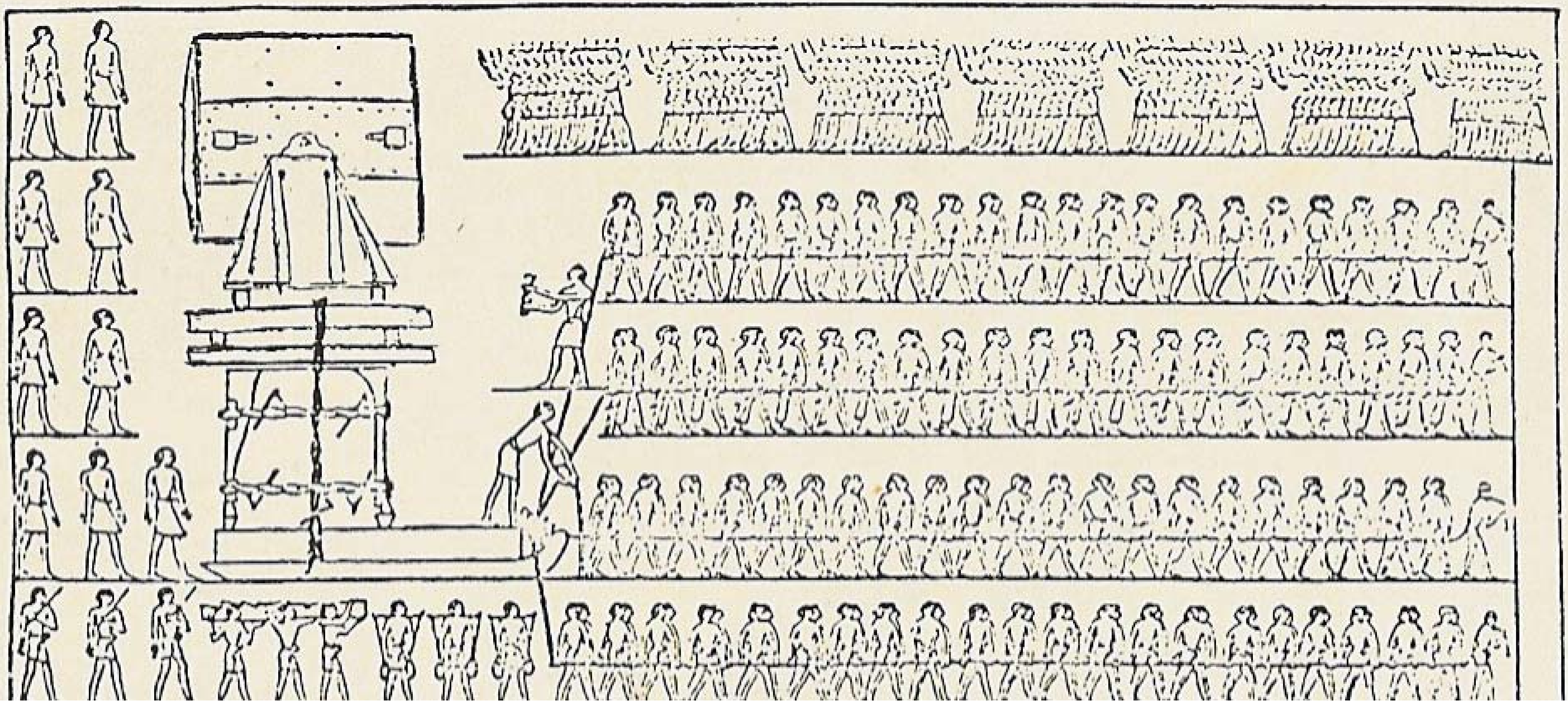


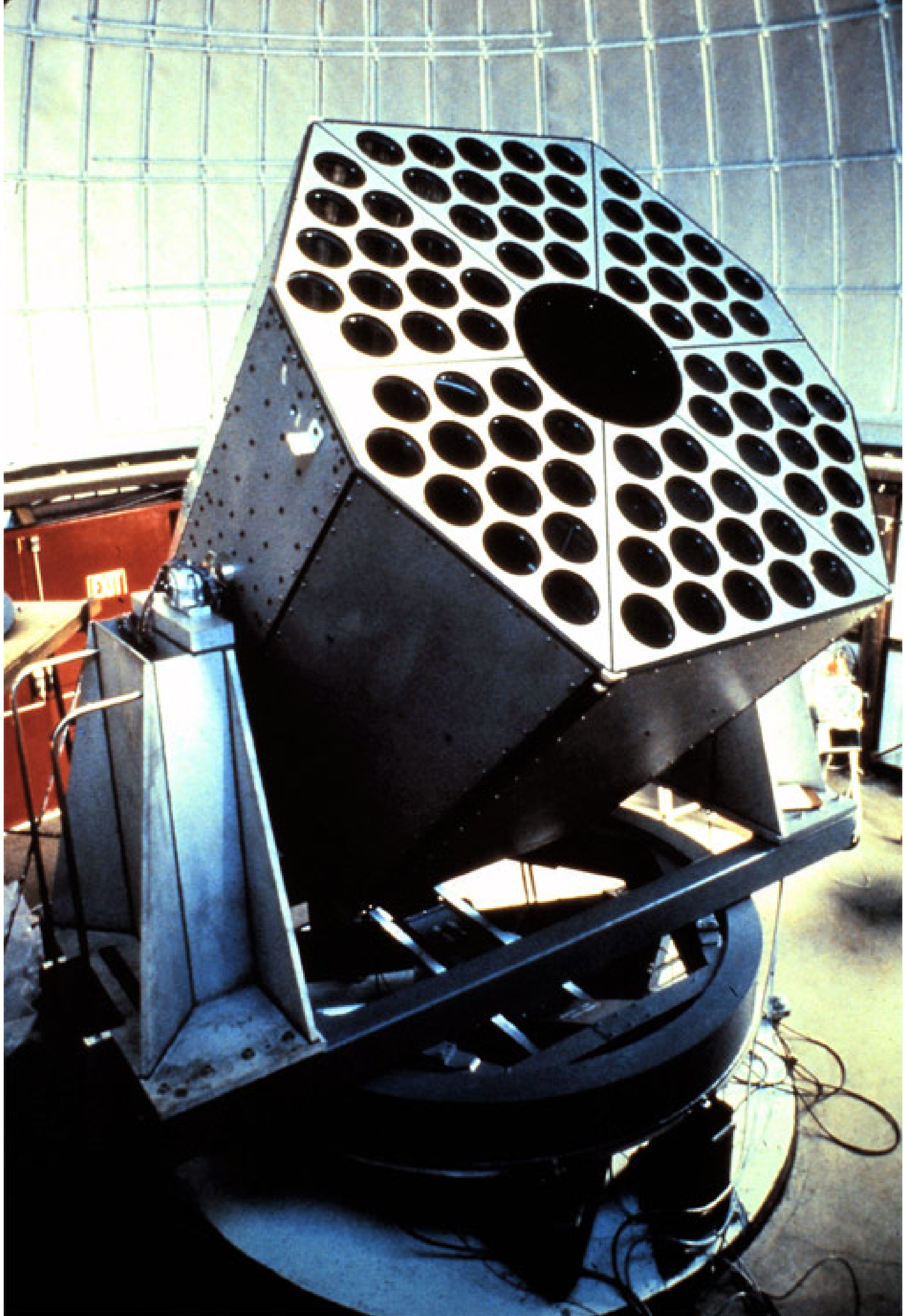

L-1
A-15
L-2
A-14
A-11

The Need for (low cost) Aperture

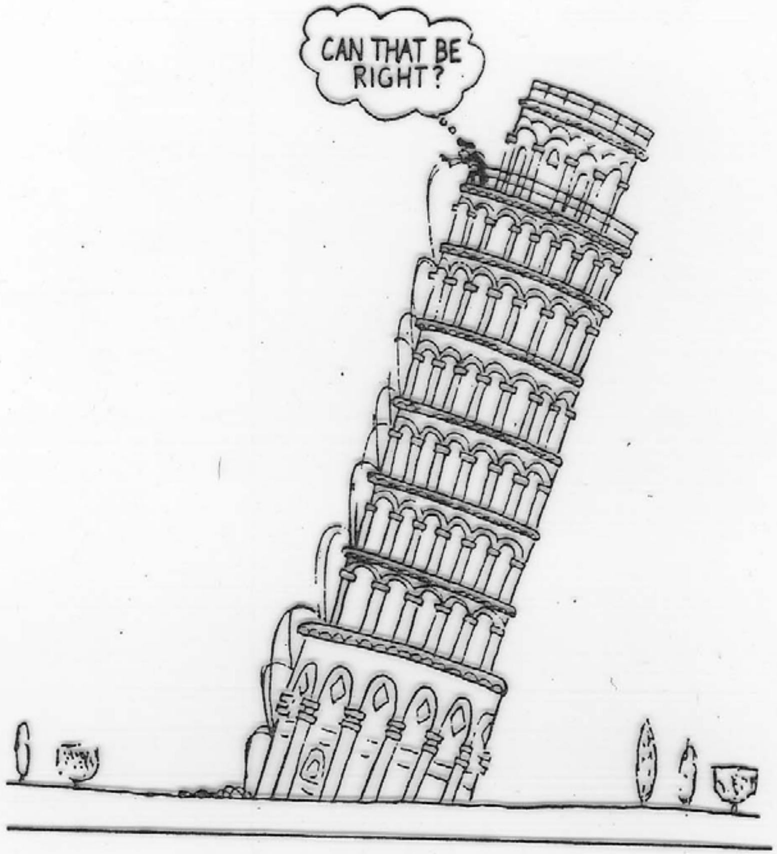



DIAPHRAGM (PINHOLE)
INTERFERENCE FILTER
COMMON FOCUS
RECOLLIMATOR
PHOTO MULTIPLIER
COLLIMATING LENS
MIRRORS
LENSES
FOCUSING MECHANISM & COLLIMATOR LENSES




EXIT

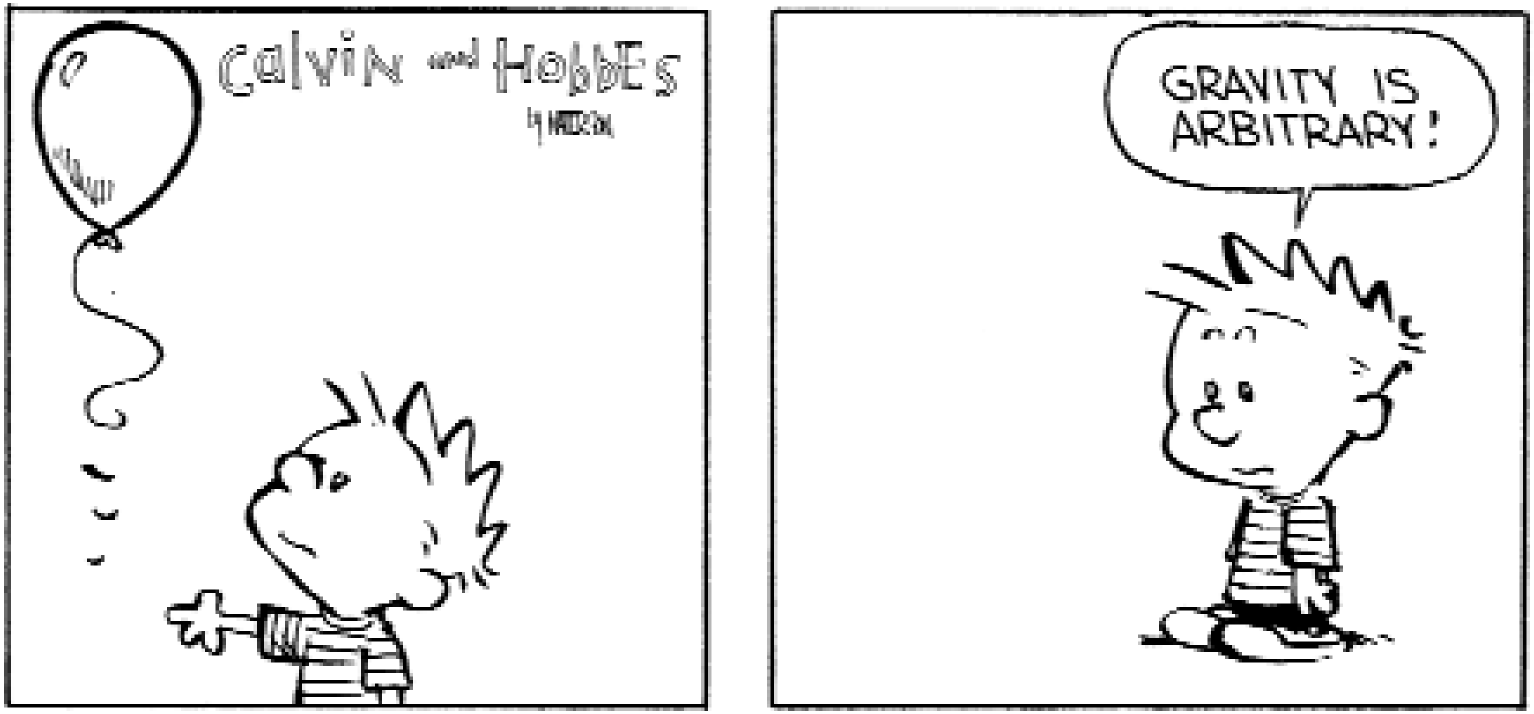
Practical Guide to Free-Fall Experiments

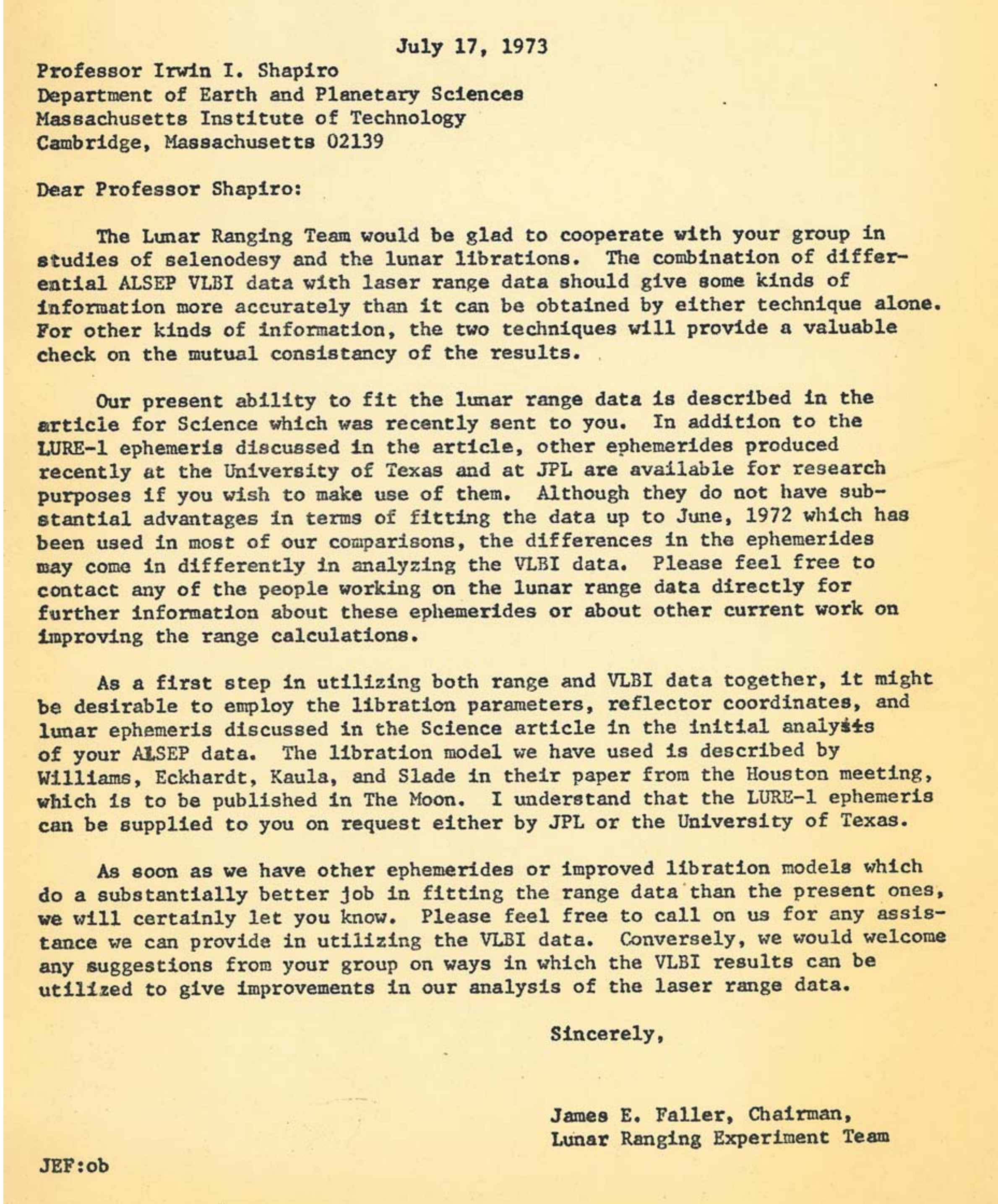


A NEW TEST OF THE EQUIVALENCE PRINCIPLE FROM LUNAR LASER RANGING*

R. H. Dicke,[1] J. G. Williams,[2] P. L. Bender,[3] C. O. Alley,[4] W. E. Carter,[5] D. G. Currie,[4], D. H. Eckhardt,[6] J. E. Faller,[3] W. M. Kaula,[7] J. D. Mulholland,[8] H. H. Plotkin,[9] P. J. Shelus,[8] E. C. Silverberg,[10] W. S. Sinclair,[2] and D. T. Wilkinson[1]

1. Princeton University, Princeton, New Jersey 08540
2. Jet Propulsion Laboratory, Pasadena, California 91103
3. Joint Institute for Laboratory Astrophysics, Boulder, Colorado 80309
4. University of Maryland, College Park, Maryland 20742
5. University of Hawaii, LURE Observatory, Kula, Maui 96790
6. Air Force Cambridge Laboratories, Bedford, Massachusetts 01731
7. University of California, Los Angeles, California 90024
8. University of Texas, Austin, Texas 78712
9. Goddard Space Flight Center, Greenbelt, Maryland 20771
10. McDonald Observatory, Fort Davis, Texas 79734


Calvin and Hobbes
by WATTERSON
GRAVITY IS ARBITRARY!



July 17, 1973

Professor Irwin I. Shapiro
Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Shapiro:

The Lunar Ranging Team would be glad to cooperate with your group in studies of selenodesy and the lunar librations. The combination of differential ALSEP VLBI data with laser range data should give some kinds of information more accurately than it can be obtained by either technique alone. For other kinds of information, the two techniques will provide a valuable check on the mutual consistancy of the results.

Our present ability to fit the lunar range data is described in the article for Science which was recently sent to you. In addition to the LURE-1 ephemeris discussed in the article, other ephemerides produced recently at the University of Texas and at JPL are available for research purposes if you wish to make use of them. Although they do not have substantial advantages in terms of fitting the data up to June, 1972 which has been used in most of our comparisons, the differences in the ephemerides may come in differently in analyzing the VLBI data. Please feel free to contact any of the people working on the lunar range data directly for further information about these ephemerides or about other current work on improving the range calculations.

As a first step in utilizing both range and VLBI data together, it might be desirable to employ the libration parameters, reflector coordinates, and lunar ephemeris discussed in the Science article in the initial analysis of your ALSEP data. The libration model we have used is described by Williams, Eckhardt, Kaula, and Slade in their paper from the Houston meeting, which is to be published in The Moon. I understand that the LURE-1 ephemeris can be supplied to you on request either by JPL or the University of Texas.

As soon as we have other ephemerides or improved libration models which do a substantially better job in fitting the range data than the present ones, we will certainly let you know. Please feel free to call on us for any assistance we can provide in utilizing the VLBI data. Conversely, we would welcome any suggestions from your group on ways in which the VLBI results can be utilized to give improvements in our analysis of the laser range data.

Sincerely,

James E. Faller, Chairman,
Lunar Ranging Experiment Team

JEF:ob

Verification of the Principle of Equivalence for Massive Bodies*

Irwin I. Shapiro and Charles C. Counselman, III
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Robert W. King
Air Force Cambridge Research Laboratories, Bedford, Massachusetts 01731

(Received 10 December 1975)

Analysis of 1389 measurements, accumulated between 1970 and 1974, of echo delays of laser signals transmitted from Earth and reflected from cube corners on the Moon shows gravitational binding energy to contribute equally to Earth's inertial and passive gravitational masses to within the estimated uncertainty of 1.5%. The corresponding restriction on the Eddington-Robertson parameters is $4\beta - \gamma - 3 = -0.001 \pm 0.015$. Combination with other results, as if independent, yields $\beta = 1.003 \pm 0.005$ and $\gamma = 1.008 \pm 0.008$, in accord with general relativity.

Verification of the principle of equivalence has been of concern to physicists at least since the time of Ioannes Grammaticus in the 5th Century.[1] Laboratory experiments performed over the past 300 years have allowed increasingly stringent limits, from 1 part in 10^3 to 2 parts in 10^{12}, to be placed on the independence on composition and size of the ratio of the inertial to the passive gravitational masses of diverse objects.[2] However, despite their impressive accuracy, these experiments fail utterly to test whether gravitational binding energy contributes equally to inertial and gravitational mass. For a meter-sized laboratory object, the gravitational binding energy represents only about 1 part in 10^{23} of the total energy, about eleven orders of magnitude too small to detect with present laboratory techniques. To test this aspect of the principle of equivalence, the cornerstone of general relativity, it is necessary to utilize planetary-sized bodies since the ratio, Δ, of the magnitude of the gravitational binding energy to the total energy scales as the square of a typical length. For a homogeneous sphere, $\Delta = 0.8\pi G\rho R^2/c^2$, with G the constant of gravitation, c the speed of light, ρ the density, and R the radius.

To verify the principle of equivalence or to detect a violation for such massive bodies, one must monitor their orbital behavior. However, without independent measurements of mass, three or more bodies are required to detect a violation. Nordtvedt[3] pointed out that for this purpose the Earth-Moon-Sun system would be useful since laser measurements[4] of the Earth-Moon separation, made possible by the optical corner reflectors on the moon, would allow a significant test to be made.

To describe the orbital effects of a violation, we consider the simplified Newtonian equations of motion for the geocentric orbit of the Moon, neglecting terms of order Δ^2 and perturbations of all bodies except the Sun:

PHYSICAL REVIEW LETTERS

VOLUME 36 15 MARCH 1976 NUMBER 11

New Test of the Equivalence Principle from Lunar Laser Ranging*

J. G. Williams, R. H. Dicke, P. L. Bender, C. O. Alley, W. E. Carter, D. G. Currie, D. H. Eckhardt,
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E. C. Silverberg, W. S. Sinclair, M. A. Slade, and D. T. Wilkinson

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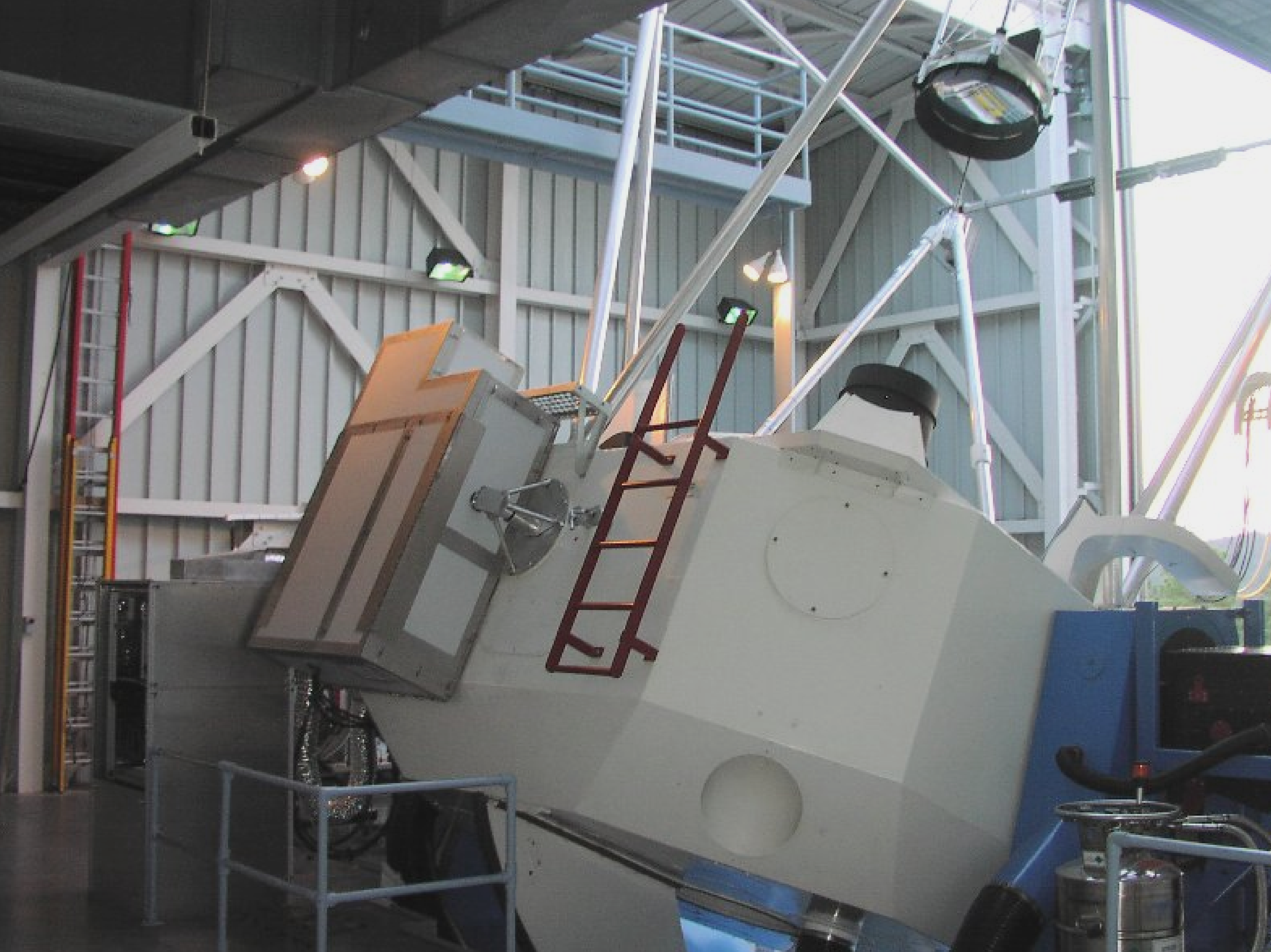
Air Force Cambridge Research Laboratories, Bedford, Massachusetts 01731, and
University of California, Los Angeles, California 90024, and University of Texas
McDonald Observatory, Austin, Texas 78712, and Goddard Space Fight Center,
Greenbelt, Maryland 20771

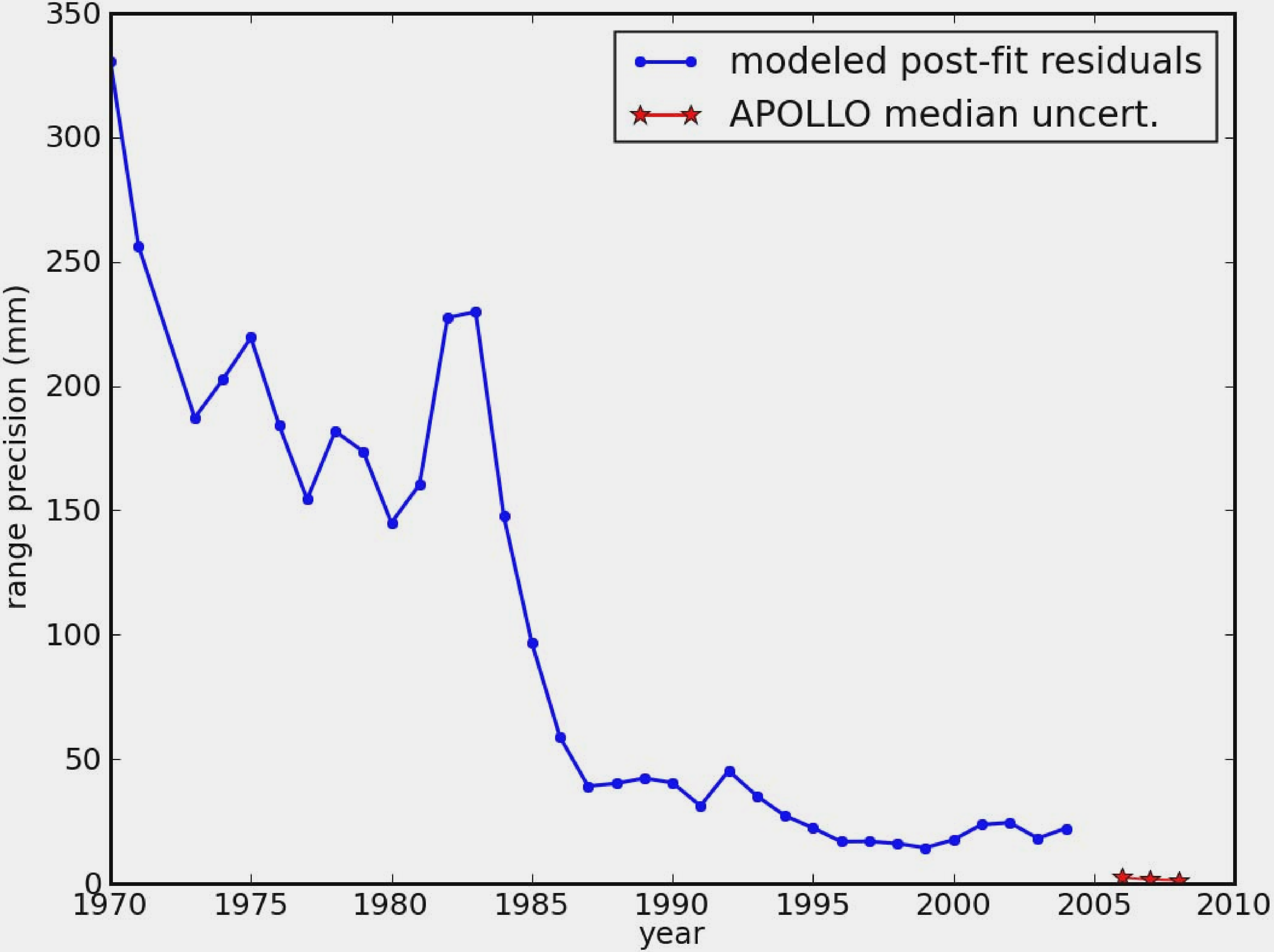
(Received 8 December 1975)

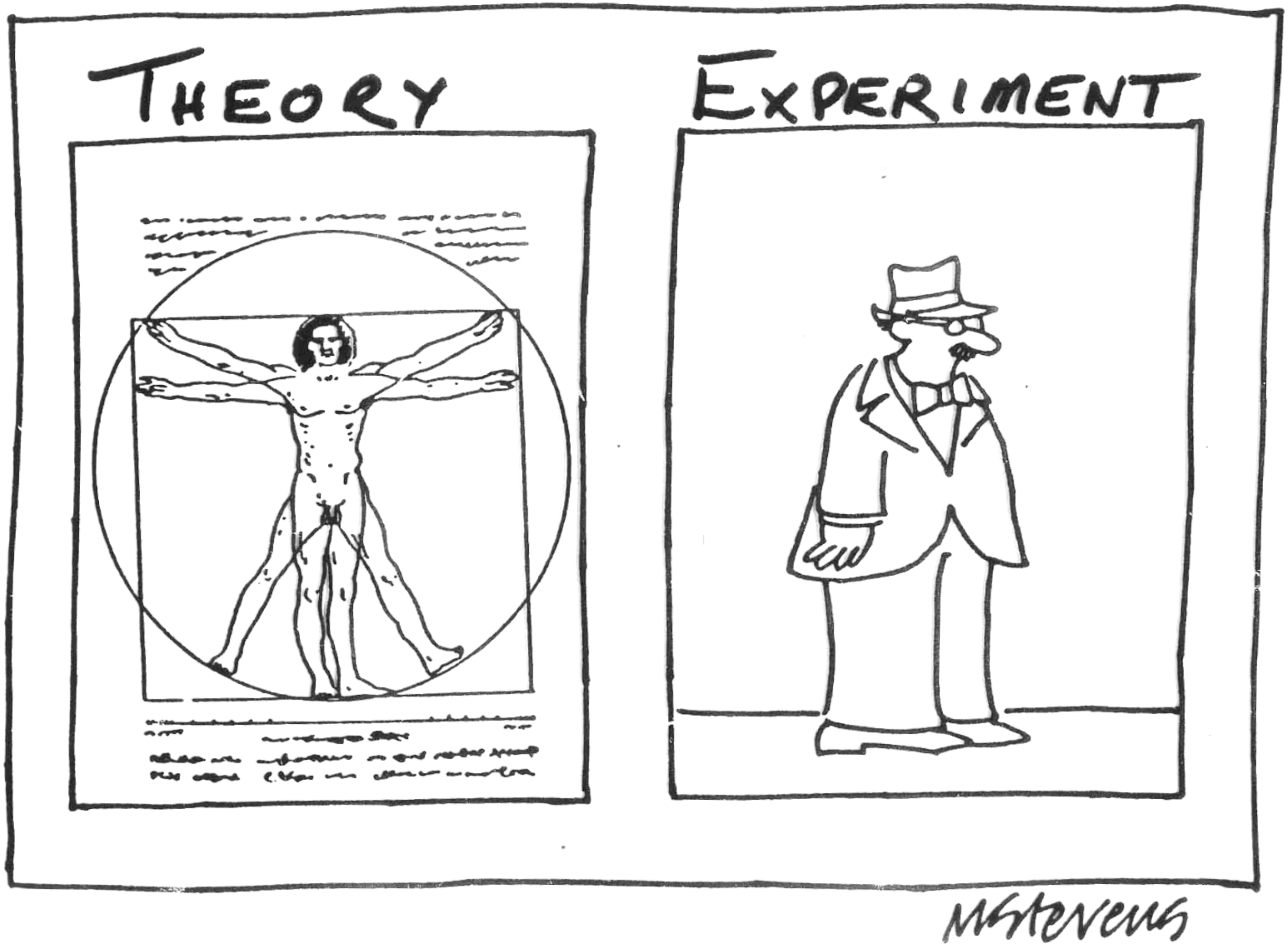
An analysis of six years of lunar-laser-ranging data gives a zero amplitude for the Nordtvedt term in the Earth-Moon distance yielding the Nordtvedt parameter $\eta = 0.00 \pm 0.03$. Thus, Earth's gravitational self-energy contributes equally, ±3%, to its inertial mass and passive gravitational mass. At the 70% confidence level this result is only consistent with the Brans-Dicke theory for $\omega > 29$. We obtain $|\beta - 1| \lesssim 0.02$ to 0.05 for five-parameter parametrized post-Newtonian theories of gravitation with energy-momentum conservation, or $|\beta - 1| \lesssim 0.01$ if only β and γ are considered.

It was pointed out by Dicke in 1961 that the ratio of the gravitational mass to inertial mass for astronomical bodies could be slightly different from unity if the gravitational self-energy of a body varied with its position in the gravitational potential of another body.[1] When the total mass of a test body is a function of its position in a static gravitational field, an anomalous "gravitational" force must act on the body if energy is to

equivalence principle in the metric theories of gravity.[4] To do this, he extended the parametrized post-Newtonian (PPN) formulation of metric theories and calculated for the first time how the deviation from unity of the ratio of gravitational mass to inertial mass would depend on the various parameters. He showed that the results correspond to a new aspect of relativistic gravity which has not been measured in other gravitation-




modeled post-fit residuals
APOLLO median uncert.
range precision (mm)
350
300
250
200
150
100
50
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
year


THEORY
EXPERIMENT
MStevens


7
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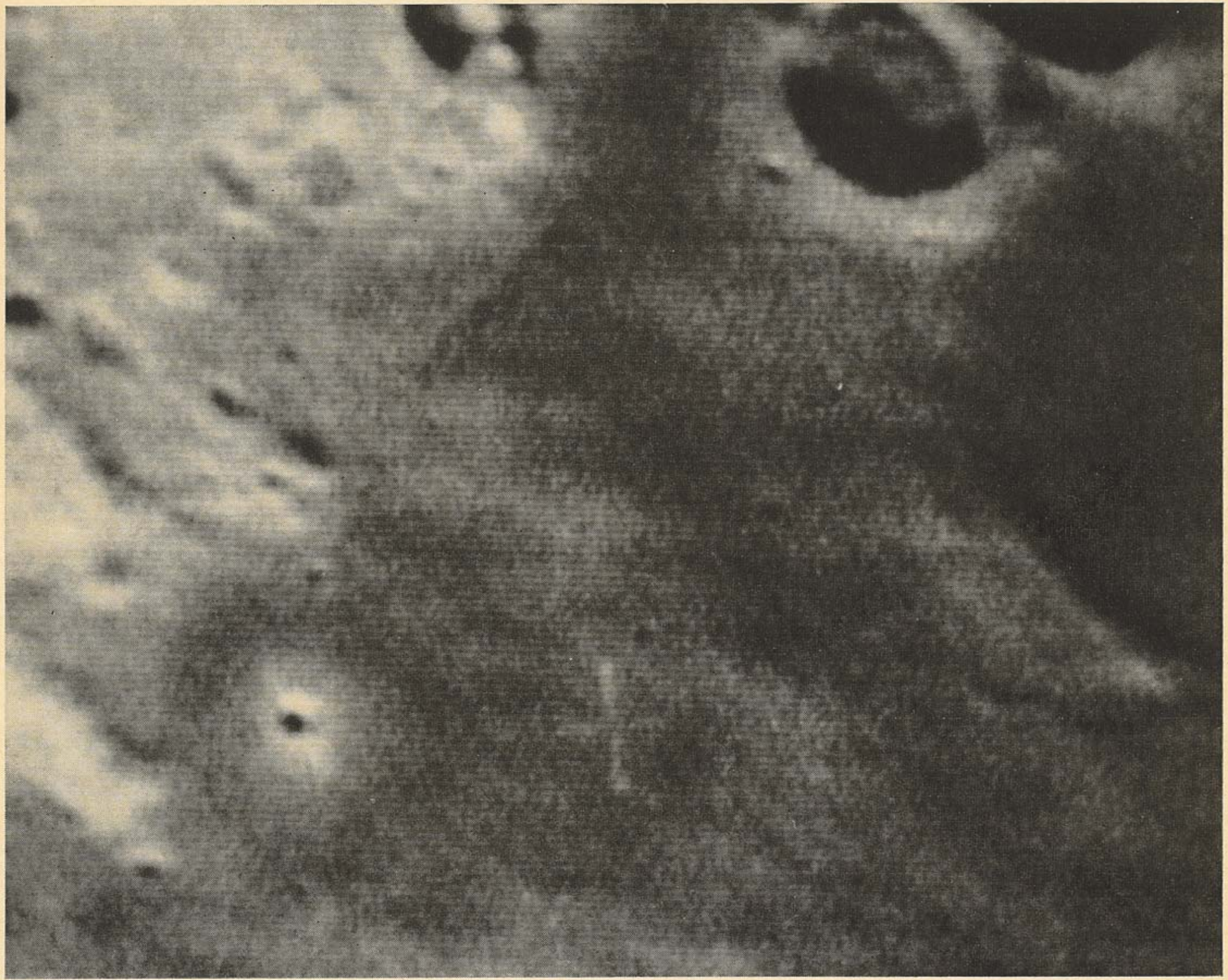
Frascino



INVISIBLE TARGET of the lunar-ranging experiment was the retroreflector array at the *Apollo 11* landing site in the Sea of Tranquillity. The guidance system that aimed a laser beam at the target through the Lick telescope incorporated a television camera, and this is a television view obtained while the astronauts were still on the moon. The landing site was located with respect to known craters. When the telescope was pointed so that a reticle fell on one of these craters, Moltke (*bottom left*), the target reticle was over the presumed position of the landing site (*bottom center*) some 25 miles away. (When this picture was taped, the data were not yet refined and so the target reticle is slightly misplaced.) In order to confirm the aim, a small portion of the laser light was returned to the television camera by retroreflectors in the telescope, so that a bright spot was superposed on the target reticle every time the laser fired.

E. Cernan

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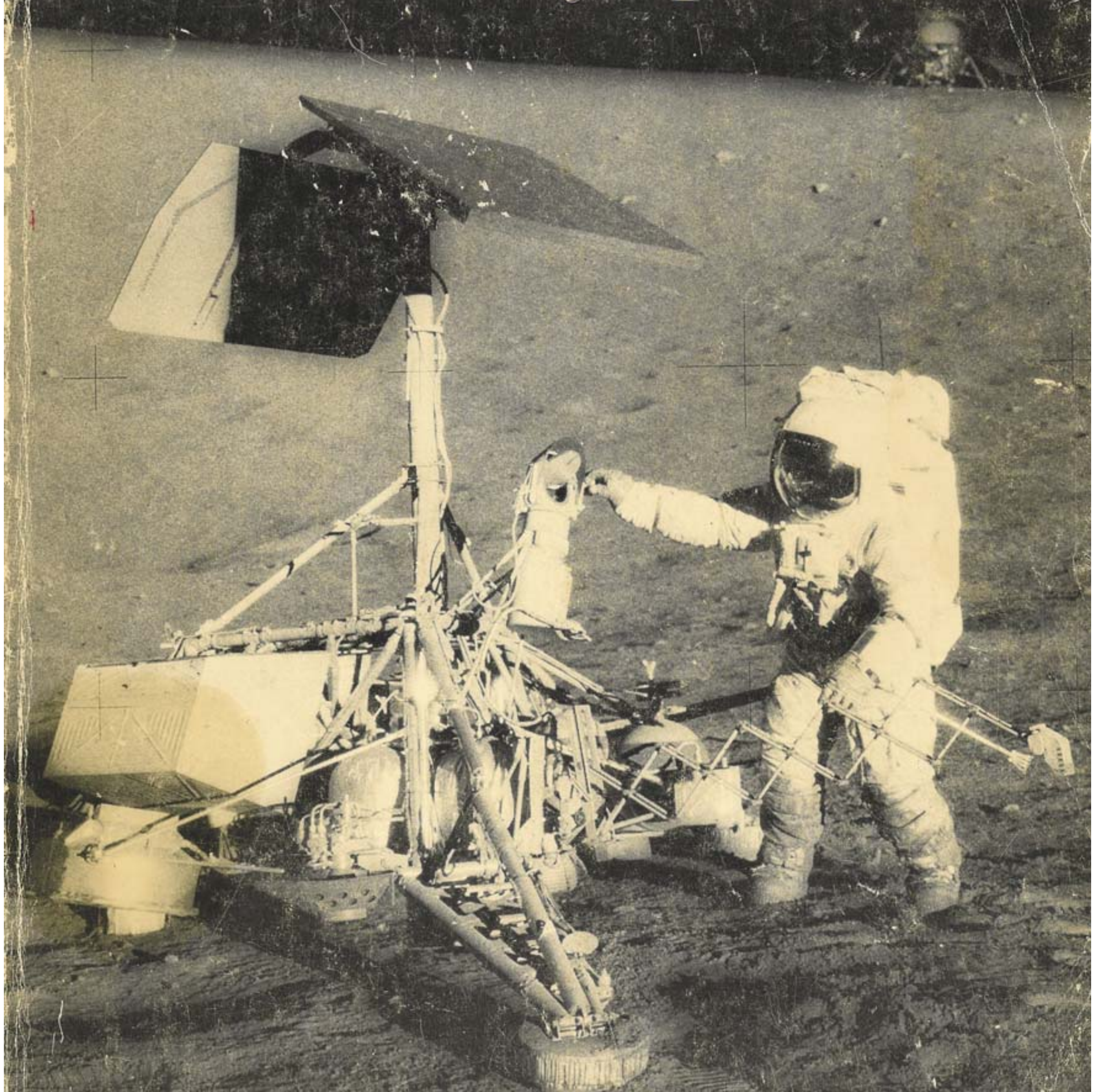
U.S.A.

Analysis of Surveyor 3 material and photographs returned by Apollo 12



II. Summary and Conclusions

N. L. Nickle and W. F. Carroll

The successful return of the Surveyor 3 hardware, lunar soil, and photographs taken by the Apollo 12 astronauts permitted 36 studies to be made by more than 80 investigators.

Chapter III contains the significant engineering results obtained from these studies. Chapters IV through XI contain the results of the scientific investigations. Because the papers were written individually by members of the investigating teams and therefore are presented in a different format than are chapters I through III, some redundancy or differences in interpretation may occur.

This chapter is a summary of the engineering and scientific results derived from the investigations.

Engineering Results

Results of the engineering investigations were essentially "nonspectacular"; the primary value lies in the fact that no failures or serious adverse

ment with laboratory simulations. The discoloration was found to be subject to photo-induced oxygen bleaching. This bleaching was responsible for a considerable change in color during the several months of exposure since return to Earth. Organic contamination is not a significant factor in the observed discoloration of the external surfaces.

Almost all exposed surfaces on the camera were partially covered with a fine layer of lunar dust. Substantial variations existed in the quantity and apparent particle size of dust on the various surfaces. The dust distribution indicates that the fines were disturbed and implanted upon the spacecraft primarily by the initial Surveyor landing and by the approach and landing of the Apollo 12 Lunar Module (LM). The presence of dust, even in very small quantities, can have a significant effect on temperature control and optical performance of hardware on the lunar surface.

> “More things are known than are actually true.”
>
> J. R. Pierce

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LUNAR LASER RANGING
REMINISCENCES

While on leave at Harvard in 1954-55, I considered the experimental basis of general relativity, Einstein's theory of gravitation. I concluded that the observational basis was thin and that much more was needed, particularly a modern high precision version of the Eotvos experiment. This experiment was started at Priinceton in 1955. Problems were encountered and many students, post docs and faculty contributed to their solutions.

Among the interests of our research group was Dirac's Cosmology and its implication of a decreasing gravitational constant, Mach's principle and the scalar-tensor theory developed in collaboration with Carl Brans.

The gravitation research group would meet in the evening once a week to discuss research ideas, some wild and some not so wild. One night testing for a decreasing gravitational constant was proposed using a zero drag satellite orbiting the earth and measuring the orbital period. The period was to be measured by reflecting a light pulse from a corner reflector carried on the satellite. The laser had not yet been developed and we had in mind using a flash lamp for illumination. With the development of the laser it became feasible to eliminate the artificial satellite and use the moon instead. Jim Faller first suggested this and I remember that he brought a corner reflector mounted in a rubber ball to one of the evening meetings to show how the experiment might be done. The ball could be dropped from a lunar lander and the ball would roll to point the reflector upward.

Some years later, after several members of the group had left Princeton, a number of us met at a Physical Society meeting to discuss the possibility of proposing such an experiment to NASA. We decided that some one person should take the responsibility of proposing the experiment and Carroll Alley was urged to do this. Alley was successful. Later an advisory committee was established with members from both inside and outside the Princeton group.

A high point in my memory of the Lunar Laser Ranging program is the night that reflected optical pulses were first observed. After the first set of corner reflectors had been left on the moon at the time of the first lunar landing, attempts were made at two different observatories to observe light pulses from the reflectors, using large telescopes, especially instrumented for the job. One of these efforts, directed by Jim Faller, used the large telescope of the Lick observatory on Mt. Hamilton. The other, directed by Carroll Alley, used a large telescope of the University of Texas.

For several days neither team was successful. The situation was desperate for the allotted time at the Lick observatory was nearly exhausted. I had not been involved with either group but happened to be spending a month at the Lick observatory on the Santa Cruz campus. On our last night I visited the telescope. Jim showed me the instrument details and he convinced me that everything was well tested and working. I spent the rest of the night in the control room looking for photon counts above the noise in the range channels. I like to believe that, in some small way, my good luck contributed to the success of that night's observations.

And what role did the Lick observations play…? They contributed an important "existence theorem" that the array was working!


PEANUTS
by SCHULZ
THIS IS HOPELESS!
A BLOODHOUND COULDN'T FIND ANYTHING OUT HERE!
I CAN'T FIND THE BALL!
WADDYA MEAN, PICK IT UP?!
HOW DO YOU EXPECT ANYONE TO FIND A BALL IN WEEDS LIKE THESE? WHAT DID YOU HIT IT OUT HERE FOR?
IT'S IMPOSSIBLE! OF COURSE, I'M LOOKING! I SAID I CAN'T FIND IT! IF I COULD FIND IT, WOULD I STILL BE OUT HERE?
THIS IS HOPELESS! NOBODY COULD FIND ANYTHING OUT HERE! YOU COULDN'T FIND A BATTLESHIP OUT HERE IF IT..
8-3
..WAIT A MINUTE...
I FOUND IT...
SCHULZ

Analysis of lunar ranges gives information on orbit, gravitational physics, geodesy, geophysics and lunar science.

Einstein’s general relativity is confirmed. Earth rotation and station positions and motions are measured. Lunar tides are measured and fluid core is detected.

Ken Nordtvedt described the LLR as “the near-complete relativistic gravity experiment.”

Irwin Shapiro once described the Lunar Laser Ranging Experiment as NASA’s “most cost effective experiment.”

Henry Cavendish, were he alive today, would describe the Lunar Laser Ranging Experiment by using the same words he used in regard to his (1798) “Experiment to Determine the Density of the Earth” namely, “The apparatus is very simple.”

And were Einstein alive today, he would simply say, in spite of its apparent simplicity, “The Lunar Laser Ranging Experiment is a Thick Board!”

“I HAVE LITTLE PATIENCE WITH SCIENTISTS WHO TAKE
A BOARD OF WOOD, LOOK FOR ITS THINNEST PART, AND
DRILL A GREAT NUMBER OF HOLES WHERE DRILLING IS EASY.”

ALBERT EINSTEIN